BRIQUETTE COMBUSTION IN RESIDENTIAL HEATERS

by

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DECLARATION

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ABSTRACT

This thesis reports research into the use of brown coal briquettes in domestic heating appliances. The performance of three commercially available heaters was determined and a prototype heater with improved performance was designed and tested.

Testing of the commercially available heaters when fuelled with briquettes, wood, or a mix of the two, involved safety (in accordance with AS2918), efficiency, power, creosote, burn time, ash and particulate emission measurements. Results showed strong dependence on heater design, with one design showing reasonable performance ; efficiency of 58% and 5 grams per hour emission rate, whereas the least satisfactory had an efficiency of 54% with an emission rate of 36 grams per hour.

The information gained from testing these heaters and conclusions drawn from the scientific and technical literature was used to design and construct a briquette burning heater. The prototype built was a downdraft heater with an inbuilt gravity feed fuel hopper. The emission rate of the final prototype was found to be 3.54 grams per hour, the average overall efficiency was 69% and the power output range was 3 to 13 kW. These values were better than the original parameters aimed for when designing the heater.

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PART ONE

1.1 INTRODUCTION

The past decade has seen a major revival in the popularity of wood burning residential heaters. Prior to 1978 the popularity of such appliances in Australia was decreasing. The sudden reversal in their popularity was probably due to the oil crisis at the time, which led to dramatic rises in the the price of oil. The resulting increase in consumer demand naturally led to greater competition between manufacturers and new manufacturers entering the market.

Such an increase in heater popularity also increased the public's need for fuel and as a consequence over the years, what was once a cheap and abundant source of energy has become more expensive and harder to obtain. This has led researchers and manufacturers to direct their efforts to designing heaters that are efficient in delivering the most energy to the space to be heated.

Initially, reseach and development was slow because of a general lack of understanding of the complex wood combustion process. Research papers which had long been gathering dust were "rediscovered" and new laboratory techniques were developed to investigate earlier claims in woodheater design and operation.

In addition to improving the efficiency of woodheaters the polluting effect of the particulate emissions (smoke) has also come under close scrutiny. This is particularly so in the USA where the Environmental Protection Agency (EPA), through governmental legislation, has placed stringent boundaries on the quantity of smoke a particular heater can emit over a given time. Although no such law exists in Australia, manufacturers are becoming more aware that such legislation may soon be introduced.

At present the only legislation that exists is the requirement that heaters be tested for clearances from combustibles such as walls and floors as described in Australian Standard AS2918.

Most research on efficiency and emissions in Australia has focussed on the use of wood as the fuel source and as such very little has been done on other fuels. One such fuel, which has been the focus of this research, is the brown coal briquette manufactured by the State Electricity Commission of Victoria and distributed by the Coal Corporation of Victoria.

The aim of this thesis was to gain a better understanding of brown coal briquette use in solid fuel appliances. Since the majority of appliances on the market are intended primarily as wood burners, a study was needed to determine what features were nesessary for efficient briquette combustion. By identifying these features, and obtaining performance data, a suitable approach to marketing briquettes as a domestic fuel in Australia could be achieved. Furthermore these features were to be incorporated into a heater, to be built, which would hopefully perform better than its wood burning counterparts when fuelled with briquettes.

This thesis is set out into two parts. The first describes the methods and results obtained from various physical tests conducted on selected woodheaters when fuelled with briquettes, firewood and briquette-firewood mixes. The second part reports on the constuction and testing of a briquette-burning heater which was designed using the information gained as to what conditions were best suited for briquette combustion.

The physical measurements carried out included heat output, efficiency, particulates emissions, burn times, creosote formation and safe wall and flue clearances. In addition to these tests, a technical workshop and seminar on solid-fuel heater testing was attended in order to gain an idea of the industry's direction in the heating market, and what standards are expected by consumers and manufacturers.

Efficiency, heat output and burn time results were carried out using wood, briquettes and wood/briquette mixes in three solid fuel heater designs. The appliance designs chosen were tested because it was thought that they would burn briquettes well, and it was considered more valuable to work with heaters that showed a good rather than a bad performance. A total of more than 40 tests comprising over 210 single fuel load cycles were conducted. Creosote and safe wall clearance tests were conducted on heater types other than those used for efficiency, emissions and heat output.

The results obtained from these tests were used to determine what features of woodheater design contribute to clean and efficient combustion of briquettes and with this information a briquette burning heater was designed, built and tested with the aim of developing a commercialy feasible heater. The results of this research constitute Part II of this thesis.

The rest of this chapter describes general background material about the tests conducted on the woodheaters and the fuel as well as basic combustion principles.

1.2 TEST FACILITIES AND METHODS

All testing was carried out in the Home Heating Laboratory at the University of Tasmania. This laboratory, which was established in 1981, is equipped for research into residential solid-fuel burning heaters and is also used for routine testing of woodheaters for manufacturers. The facilities used for assessing the performance of heaters fuelled with briquettes are briefly summarised below. More details of the actual test methods used are provided in the relevant sections of this thesis.

1.2.1 Heater Clearance Testing

A N.A.T.A. certified test enclosure designed for testing in accordance with the Australian Standard AS2918 was used for clearance testing. Arrays of thermocouples are used to measure the surface temperatures of walls, floor and ceiling when an appliance is fuelled in the prescribed way with either wood or briquettes. The test method followed was that described in the Australian Standard AS 2918, Appendix B.

1.2.2 Calorimetry Room

Measurements of heater efficiency, power output and burn time were conducted in a "ventilated" calorimetry room, described by Todd and Sawyer (1987). Heat is extracted from the well insulated room by a continuous air flow through the room. The temperature rise of the air as it passes through the room and the air flow rate are carefully monitored, as is the rate at which the fuel burns. By calculating the average power output of the heater for a cycle load using the rise in air temperature, and the mass flow rate of the air, and relating this to the known energy content of the fuel load, the efficiency of the appliance can be determined. A microcomputer is used to monitor and analyse the data.

1.2.3 Emissions Testing

Emission tests were carried out using the dilution tunnel method. This method involves collecting all emissions of a burning cycle load via a hood and tunnel system placed over the flue exit. Smoke, diluted and cooled with ambient air, is drawn into the dilution tunnel allowing any volatiles in the smoke stream to condense before a sample is taken for particulate analysis. As the diluted smoke passes through the dilution tunnel a continuous and proportional sample is drawn out and filtered. By weighing the filter paper after the test and accounting for the dilution and temperature effects, the emission rate of the appliance is calculated. These tests were conducted simultaneously with efficiency tests using the calorimetry room. A detailed description of the dilution tunnel and test methods is given by Todd, Quraishi and King (1988).

1.2.4 Creosote Measurement

Creosote is a mixture of aromatic hydrocarbons produced by pyrolysis (oxygen starved decomposition) of wood or coal. The volatiles causing creosote burn at a higher temperature than other pyrolysis products present; if conditions are such that these volatiles do not burn, the result is condensation of creosote on the cool wall of the flue.

At present there is no standard method for creosote measurement, although various methods have been devised. Since the purpose of this investigation was to compare creosote formation between coal and wood, a method had to be devised which gave consistent results so a quantitative comparison could be made.

The method used was to hang three steel plates of known surface area and weight from a wire connected to the top of the flue. Creosote was deposited on these plates which were weighed after the test was completed. For each fuel type tested, flue conditions, such as temperature, were kept as constant as possible.

1.3 PHYSICAL AND CHEMICAL PROPERTIES OF BRIQUETTES AND WOOD

Brown coal, or lignite, from which briquettes are made, has some properties which are similar to wood and some which are more like the anthracitic coals. The relatively high volatile content of briquettes is one important parameter which likens it to wood. A few of the properties of briquettes and wood which are likely to have an influence on the way they will burn in a residential heater are listed in Tables 1.1 and 1.2.

Table 1.1

Selected Physical and Chemical Properties of Briquettes and Wood. (Figures based on measurements made during the test program and information provided by the Coal Corporation of Victoria.)

	Briquettes	Eucalyptus (air dry)
Calorific value (gross)	22.53MJ/kg	16.0MJ/kg
Moisture (% of wet mass)	13%	10-20%
Density	1.37g/cm^3	0.85g/cm^3
Ash	1.3%	<0.5%
Surface area/mass ratio *	1.56cm^2/g	0.76cm^2/g
Piece mass (approximate)	80g	1 kg
Volatiles $	44.1%	70%
Fixed carbon $	41.6%	14.6%

* The surface area/mass ratio for the firewood assumes cylindrical logs with 90mm diameter and 225mm length. It ignores surface roughness of the logs. This approximates the logs used in the tests. The briquettes have dimensions nominally 58 x 37 x 43 mm.

$ The volatile matter is determined by heating a sample of the fuel in a covered crucible for 7 minutes at 950 C. The loss in weight, minus the moisture, represents the amount of gaseous constituents produced by the decomposition of the fuel substance. Fixed Carbon is determined by subtracting moisture, volatile matter and ash.

TABLE 1.2

Ultimate Analysis of Briquettes and Firewood (oven dry, ash free basis). Briquette data: State Electricity Commission of Victoria, unpublished data sheet. Wood data: Average figures for E amygdalina and E globulus from Hydro-Electric Commission, Tasmania (1986).

	Briquettes %	Firewood %
Carbon	68.0	49.5
Hydrogen	4.8	5.8
Oxygen	26.3	44.6
Nitrogen	0.5	0.1
Sulphur	0.3	0.01
Chlorine	0.1	-

1.3.1. Briquette and Wood Combustion

When briquettes or wood are heated certain chemical transformations take place which result in the release of volatile gases. These gases will burn provided the temperature is high enough and sufficient oxygen is present. These burning gases, which we see as flame, are an important part of the energy release process during wood combustion accounting for roughly two thirds of the energy. Most residential heaters on the Australian market have been designed for the combustion of wood. If briquettes are to perform well in these heaters it seems likely that the release and combustion of volatiles will be one of the key factors. The lower proportion of volatiles in briquettes (Table 1.1) might, therefore, mean poor combustion of the briquettes in these appliances. As will be demonstrated, this did not prove to be the case, and briquettes burnt well in the heaters tested.

1.3.2 Ash Content

The ash content of briquettes is considerably greater than that of wood, but at 1.3% it is still quite low compared to many coals (Tasmanian Fingal coal, for example, has over 20% ash). Briquette ash is orange brown in colour and has a low density, which is a disadvantage as it means more frequent removal from heaters, particularly as many woodheaters have small ash removal trays because of the low ash content of wood. Ash can also affect combustion of the fuel if it forms an insulating layer on the surface of the fuel, thus restricting combustion.

1.3.3 Calorific Value

The calorific value of briquettes is about 30% higher than that of air dry wood. If burn rate and combustion efficiency for wood and briquettes were the same then the greater rate of energy release might lead to much higher temperatures in heaters and higher power output. If this were extreme it could damage the heater and cause problems with safe heater clearances from walls.

1.3.4 Physical Properties

With any solid fuel the physical properties of piece size and shape, proximity to other pieces, surface area to volume ratio and density will all have a marked influence on combustion. Kindling, for example burns much faster than large logs of wood and a single log in a heater will usually not continue to burn, but two or three logs will burn without difficulty. Thus, it might be expected that the very different physical properties of briquettes and typical logs of firewood would lead to very different combustion properties.

1.4 BASIC PRINCIPLES OF WOODHEATER PERFORMANCE

1.4.1 Combustion Efficiency

One of the most important goals in designing woodheaters is achieving the highest possible overall efficiency and to do this, combustion efficiency should be at a maximum. The difficulty lies in ensuring that all the volatiles that are released are subsequently ignited, since unburnt volatiles means a loss of energy, reduced combustion efficiency, and increased pollution. Many of the gases produced during combustion have high ignition temperatures (eg. H_2:530 C, CO: 600 C, methane: 645 C. (Lange 1973)). Thus, for efficient combustion, gas temperatures must be kept high. The gases must be also be retained in the combustion zone long enough to ensure complete combustion, and have access to a sufficient supply of oxygen.

Combustion efficiency can be represented by the following equation:

$$\text{Combustion Efficiency} = \frac{\text{Heat generated in combustion}}{\text{Gross fuel energy}} \qquad 1.1$$

1.4.2 Heat Transfer Efficiency

Heat transfer efficiency is quite distinct from combustion efficiency. It is the proportion of the heat released during combustion which is transfered to the space to be heated. In most heaters the firebox itself serves as the heat exchange, sometimes a forced air system is used to increase heat transfer. Exposed flue in the living area also acts as a heat exchange.

Heat transfer efficiency can be represented by the following equation:

$$\text{Heat Transfer Efficiency} = \frac{\text{Useful heat output}}{\text{Heat generated in combustion}} \qquad 1.2$$

1.4.3 Overall Efficiency and its Theoretical Limits

The maximum possible overall efficiency is achieved when both combustion and heat transfer are complete. Although complete combustion is desirable, complete heat transfer is not.

Heat losses occur in two ways, 1) sensible heat due to the raised temperature of the flue gases and 2) latent heat associated with the water vapour. In most domestic heaters, raised flue gas temperatures are required to induce draft. If too much heat is recovered from the heater then an inadequate draft will result, and if the the flue gases are cooled below the dew point water condensation will occur. Low flue gas temperatures also lead to increased creosote build up.

Consider the complete combustion of 1 kg of firewood (16.7% moisture w/w) with 100% excess air (fairly typical), a room temperature of 20 C and flue gas temperature of 200 C. The theoretical sensible heat losses are 2.2 MJ and the latent heat losses are 1.9 MJ (water results from moisture content and combustion products). The combined losses amount to almost 25% of the available energy in 1 kg of firewood (16.6 MJ/kg).(Todd 1985).

So, due to the necessity of sensible and latent heat losses, the maximum, practical overall efficiency is limited to about 75 to 80% for typical domestic heaters.

1.4.4 Types of Heater Designs

As mentioned before, an important goal of heater manufacturers has been to make their appliances more efficient. But the range of conditions under which heaters must be able to operate makes this task an unpredictable venture and, as a result, the method of designing heaters has mainly been one of trial and error. There are a number of design factors which should be incorporated into the heater product. The heater must be able to operate over a fairly wide range of power outputs, it must be convenient and safe to operate and resistant to moderate abuse. Refuelling and adjustment of controls should not be required too frequently. Recent developments in Government regulations, especially in the USA, set maximum allowable smoke emissions. The appliance also needs to be attractive in order to compete with other heaters and should be reasonably priced. Of the conventional airtight heaters on the market there are but three basic combustion configurations (Figure 1.1).

The 'S' draft, or baffled box heater, is designed so that air enters at the top of the firebox and is deflected down (over the inside of the glass panel in the door) and directly into the combustion zone. The term 'S' draft comes from the shape of the air pathway.

With the updraft design, air enters the firebox below a grate, and is drawn through the combustion zone.

The downdraft design takes air in at the top of the firebox . draws it through the combustion zone and then exits via the flue. The advantage of this system is that unburnt volatiles are drawn through the very hot charcoal combustion zone by the air draft which ensures more complete combustion.
The three basic designs give overall efficiencies of around 45-60%.(see Shelton 1983 or Todd and Wingham 1989).

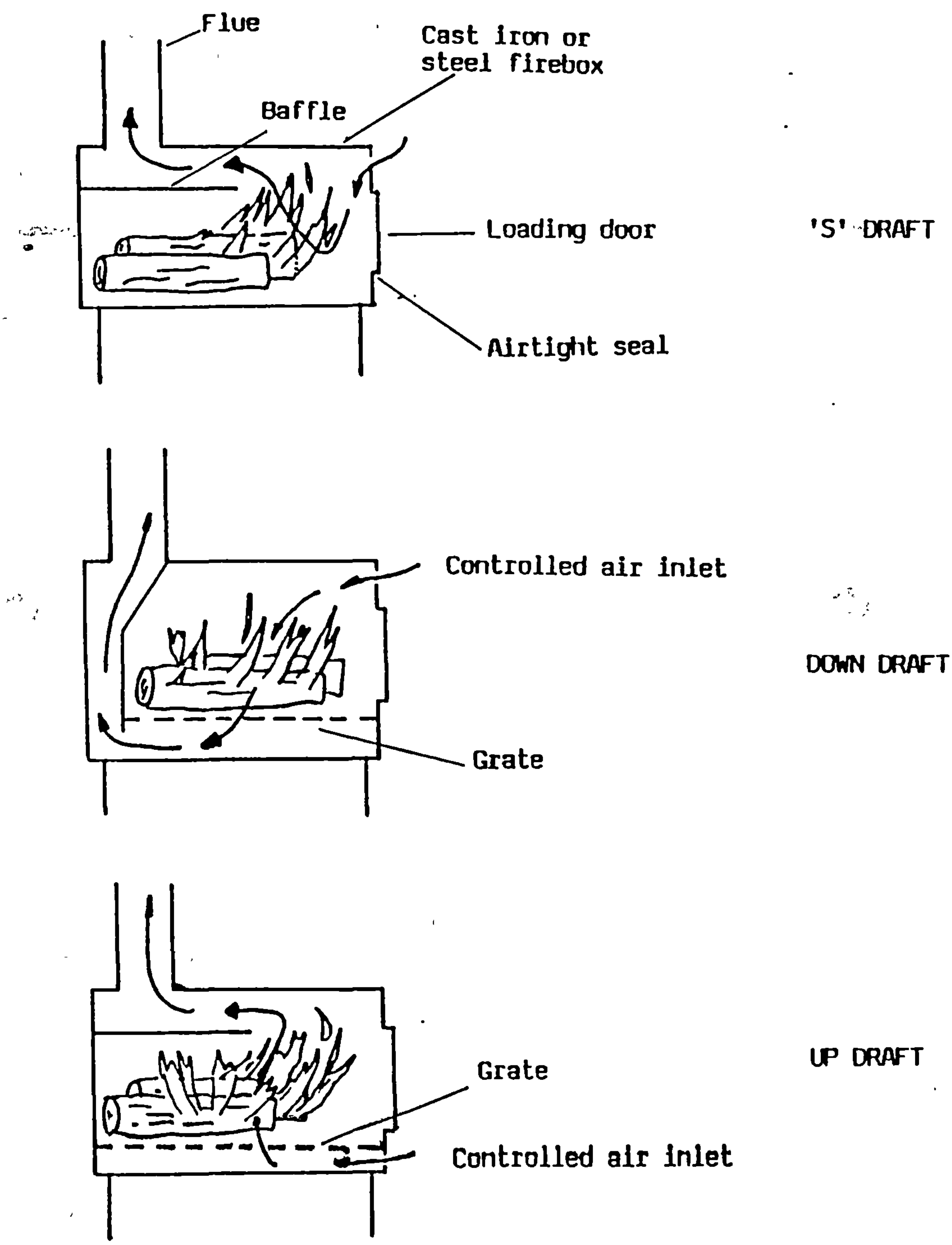


Figure 1.1. Three basic designs of combustion configurations used for woodheaters.

2 SAFETY CLEARANCE TESTS

Australian Standard AS2918 sets installation requirements for solid-fuel burning appliances (Standards Association of Australia 1987). The Standard has been called up in Building Regulations in most states and offers a uniform national requirement for heater installation. Gradually, the alternative installation requirements, which differ from state to state, are being phased out of Building Regulations. Within a few years, heater manufacturers and importers will have to comply with the Australian Standard in order to market their appliances in Australia. Already, most appliances on the market have installation instructions which reflect the requirements of the Standard.

AS2918 requires any appliance which is to be used with either coal or briquettes at reduced clearances to be tested with briquettes. If such an appliance has not been tested for reduced clearances with briquette fuel it must be installed in accordance with the 'worst case' requirements specified in the Standard. These 'worst case' requirements cover wall clearances, hearth design and flue design. Most heaters on the market have been designed to allow safe installation at considerably reduced clearances and hearth dimensions. In order to take advantage of these design features, an appliance must be tested in accordance with the test procedure set down in Appendix B of the Standard.

Any appliance that is to be used with briquettes or a briquette/wood mix and installed at reduced clearances should, therefore, be tested with briquettes.

Tests done in accordance with AS2918 at the Home Heating Laboratory over several years have shown that some designs of heater will run hotter with briquettes than with wood, in these cases it is the briquette fuel that determines the minimum safe clearance. In other designs of heater the reverse is true. The results of tests on particular models of heaters tested under contract are confidential and cannot be reproduced in this report. For this reason, three different designs of heater were tested as part of this research to demonstrate the importance of safety testing with briquettes.

The tests conducted here show the two extremes which have been encounted when testing various heater designs. It is impractical to test all possible designs but it is important to realise that the use of briquettes in some designs is unlikely to affect clearances while in some others it will. Even though some designs will probably not be affected with respect to safety clearances this will not remove the requirement for clearance testing of individual heater models.

2.1 Appliances Tested

A total of six tests were conducted on three appliances as follows:

(i) One heater was a radiant heater with the firebox divided into a baffle chamber and fuel chamber. The firebox had no grate and the air intake was controlled by a sliding plate situated above the door. The combustion air forms an air wash down the inside surface of the ceramic-glass window in the fuel loading door. This overfire air combustion system is common to many of the popular models of heaters.

This appliance was tested with 100% wood and 100% briquettes under otherwise identical conditions.

(ii) A basket grate was installed in the radiant heater mentioned in (i) above in order to increase the air flow around the fuel load. Such grates are commercially available and are marketed as a means of improving performance of a heater when fuelled with coal (although laboratory testing has not confirmed these claims). The heater was again tested with 100 % briquettes and 100 % wood.

(iii) The third set of tests was run with a small pot belly heater which included a grate as the firebox floor, an ash collecting area immediately below the grate, a door in the middle of the firebox and a top loading door. Air entered via the ash collecting compartment and the firebox door. This resulted in a combination of underfire and overfire combustion air flows.

Two tests were carried out on this appliance, one with wood and the other with briquettes. Both tests were conducted under identical test enclosure conditions.

2.2 Fuel

The wood used was Pinus radiata, dressed to 45 x 90 mm, with an average moisture content of 12% of the wet mass. This is within the fuel specifications given in AS2918.

Brown coal 'L' type briquettes supplied by the Coal Corporation of Victoria were used as delivered.

2.3 Test Procedure

Except for the quantity of fuel used for a single load, the test procedures were the same for each appliance.

Ignition. For all tests, ignition was achieved by using eucalyptus kindling to establish the desired ember bed before testing commenced.

High Fire. The high fire procedure for all tests was carried out according to Appendix B of Australian Standard AS2918. This meant operating the appliance under conditions which gave highest surface temperatures of the test enclosure with refuelling every 10 minutes and continuing the refuelling until all temperatures had stabilized. Refuelling meant an equal amount (mass) of fuel was added every 10 minutes such that the fuel bed was maintained between 50-75% of the firebox volume. Tests carried out using the basket grate resulted in a slower burn rate than the tests run without it, so a reduction in fuel mass was needed.

The briquette test on the pot belly heater was done directly after the wood test. The appliance was left to cool for 20 minutes on completion of the wood test before briquette loading commenced.

2.4 Results

Table 2.1 gives the relevant fuel data for the tests conducted on the two appliances. Table 2.2 gives the average temperature over the last hour of each test (recorded at 5 minute intervals) for selected thermocouples monitoring each surface of the test enclosure. The maximum temperature reached in the last hour of each test is also shown.

TABLE 2.1

Fuel and loading data for the safety clearance tests.

APPLIANCE	TEST No.	FUEL TYPE	MOISTURE % (w/w)	AV.LOAD WT.(kg)	LOAD RATE
1 overfire air, no grate	1	wood	11.72	1.0	10min
1 overfire air, no grate	2	briq	15.00	1.0	10min
2 overfire air, grate	3	wood	12.28	0.5	10min
2 overfire air, grate	4	briq	15.00	0.5	10min
3 underfire air, grate	5	wood	12.00	0.9	10min
3 underfire air, grate	6	briq	15.00	0.9	10min

TABLE 2.2

Average surface temperatures (degrees C) for the six tests.
Maximum temperatures are shown in brackets.

		AVERAGE SELECTED SUFACE TEMPERATURES				
TEST	FUEL	HEARTH	REAR WALL	CEILING	SIDE WALL	AMBIENT
1	wood	86(89)	79(82)	73(77)	82(84)	30(31)
2	briq	62(65)	60(62)	56(58)	60(62)	27(30)
3	wood	55(56)	54(55)	57(58)	52(53)	29(30)
4	briq	36(37)	38(40)	42(46)	36(38)	23(24)
5	wood	23(24)	99(105)	49(52)	89(93)	29(29)
6	briq	27(30)	123(128)	58(60)	118(125)	33(34)

2.5 Discussion

Appliance 1, the heater without any grate and with overfire air, gave significantly lower test enclosure surface temperatures when burning briquettes than when burning wood. These, and visual observations of the burning appliance, indicated that it is not well suited to briquette combustion. Surface temperatures, under identical test conditions, when using Pinus radiata were up to 20 degrees C higher than those obtained during briquette combustion. These results were similar to those obtained with other appliances of similar design in earlier tests. They mean that safe installation clearances are limited by wood combustion not briquette combustion.

A similar relationship can seen for the results obtained using the basket grate in the same appliance. The temperatures in these tests were lower than the corresponding 'no grate' tests due to the smaller quantity of fuel being used. No previous tests had been carried out with this firebox/grate configuration so it is not possible to generalise from these results.

For appliance 3, the pot belly heater with grate and underfire air, the results show significantly higher surface temperatures for the briquette test. This would lead to larger clearances being required for this model of heater if briquettes were to be burnt. Again, this is consistent with measurements made on other appliances which have underfire air.

The conclusion reached from these tests is that any heater which is intended to burn briquettes as well as wood, must be tested with both fuels to determine what clearances are required. Since many manufacturers recommend minimum clearances which are as small as possible (but still pass the test) it would be possible to create quite an unsafe situation if a heater, particularly a heater with underfire air, was only tested with wood but then used with coal or briquettes.

3 CREOSOTE, ASH AND EMISSIONS

This chapter deals with three different sets of measurements: creosote accumulation in flues; ash residues in fireboxes; and emissions of particulates from the flues of heaters.

Creosote deposition tests were done with wood and a wood/briquette mix because there were unconfirmed reports from some heater users that mixing briquettes with wood lowered the amount of creosote.

Measurements were done on the amount of ash left by wood or briquettes as well as the quantity of ash escaping up the flue. Ash left by combusted fuel is detrimental to the operation of the heater in two ways, firstly it is a nuisance to the user because it must be removed and disposed of and, secondly, its presence can retard combustion by forming an insulating layer around the fuel.
The quantity of ash escaping up the flue was calculated in order to assess what impact this would have on particulate emission measurements. If vast quantities of briquette ash was found to be escaping up the flue, not only would emission measurements be affected but also the relationship of the user and their neighbours when complaints are raised regarding washing on the line being covered with briquette ash.

Particulate emission (smoke) was measured because of its well known potential health risk to humans.

3.1 Creosote Measurement

Creosote is the tar-like substance that forms on the walls of chimneys and flues of solid-fuel heaters. Accumulation of creosote can cause a safety hazard. If an appreciable amount of creosote collects in the flue it may ignite, causing a dangerous chimney fire. It can also block flues causing loss of performance or smoke leakage into the living area of a home.

Creosote is a mixture of aromatic hydrocarbons produced by pyrolysis (oxygen starved decomposition) of wood or coal. The volatiles causing creosote burn at a higher temperature than other pyrolysis products present; if conditions are such that these volatiles do not burn, the result is condensation of creosote on the cool wall of the flue.

At present there is no standard method for creosote measurement. Various methods have been used by different research groups (see, for example, Maxwell, Dyer and Maples 1979 or Hone 1979). Most methods involve the collection and weighing of creosote on metal plates in the flue or metal plates forming part of the flue wall. There does not appear to be much consistency between methods, in other words, there is no absolute measure of creosote formation.

Even when using one method of collection, considerable variation in the quantity of creosote collected will occur. The causes of variations include such factors as moisture content of the fuel, fuel geometry, flue gas temperature, type of wood species and combustion rate. The design of the flue itself is also important in creosote formation. If the inner walls of the flue can be maintained at reasonably high temperatures or at the same temperature as the flue gas, then less creosote will condense. Thus, insulated flues or flues with casings vented with hot air rather than cold air will condense less creosote than uninsulated or uncased flue pipes.

Since the aim of this study was to compare creosote formation between briquettes and wood, a method had to be devised for measuring creosote formation when burning wood which gave consistent results. Then, using the same method to determine creosote formation from briquette combustion, a reasonable comparison could be made between the two.

3.1.1 Method

The method used for this investigation was to hang three steel plates of known weight and surface area from a wire connected to the top of the flue. The temperature of gas passing each probe was monitored by three thermocouples (Figure 3.1).

Seven tests were carried out using eucalyptus firewood as the test fuel and four tests using a 50/50 wood/briquette mix. To reduce the number of variables, the following parameters were kept constant for each test:

Flue gas temperatures
Weight of fuel burnt
Time of exposure of the metal plates

The flue gas temperatures were kept as constant as possible by adjusting the combustion air control. In this way the rate of combustion could also be controlled. By monitoring the temperature of one probe position and adjusting the air flow accordingly, it was anticipated that the gas temperatures at the other two probes would also remain constant.

The quantity of fuel used was recorded before each test and any remaining fuel was weighed to determine the amount burned. The probes were removed before combustion of all the fuel was complete since constant temperatures were difficult to maintain towards the end of a burn cycle.

The amount of creosote deposited was calculated as a function of surface area, so the size of each probe was not a critical factor.

The appliance used for all these tests was a firebrick baffled, radiant heater with an air inlet positioned above the door, and no grate (S draft design).

Eucalyptus kindling was used to ignite the fire. When a base of burning charcoal was established, approximately 5kg of Eucalyptus or the 50/50 fuel mix was added and the door left open for 10 to 15 minutes so the fire could establish. Then the door was closed and the air inlet adjusted so a temperature reading of 85 to 95 C was maintained at thermocouple number 3. At this point the steel plates were lowered into the flue and the time recorded. Continual monitoring of the flue gas temperature and air inlet adjustment were

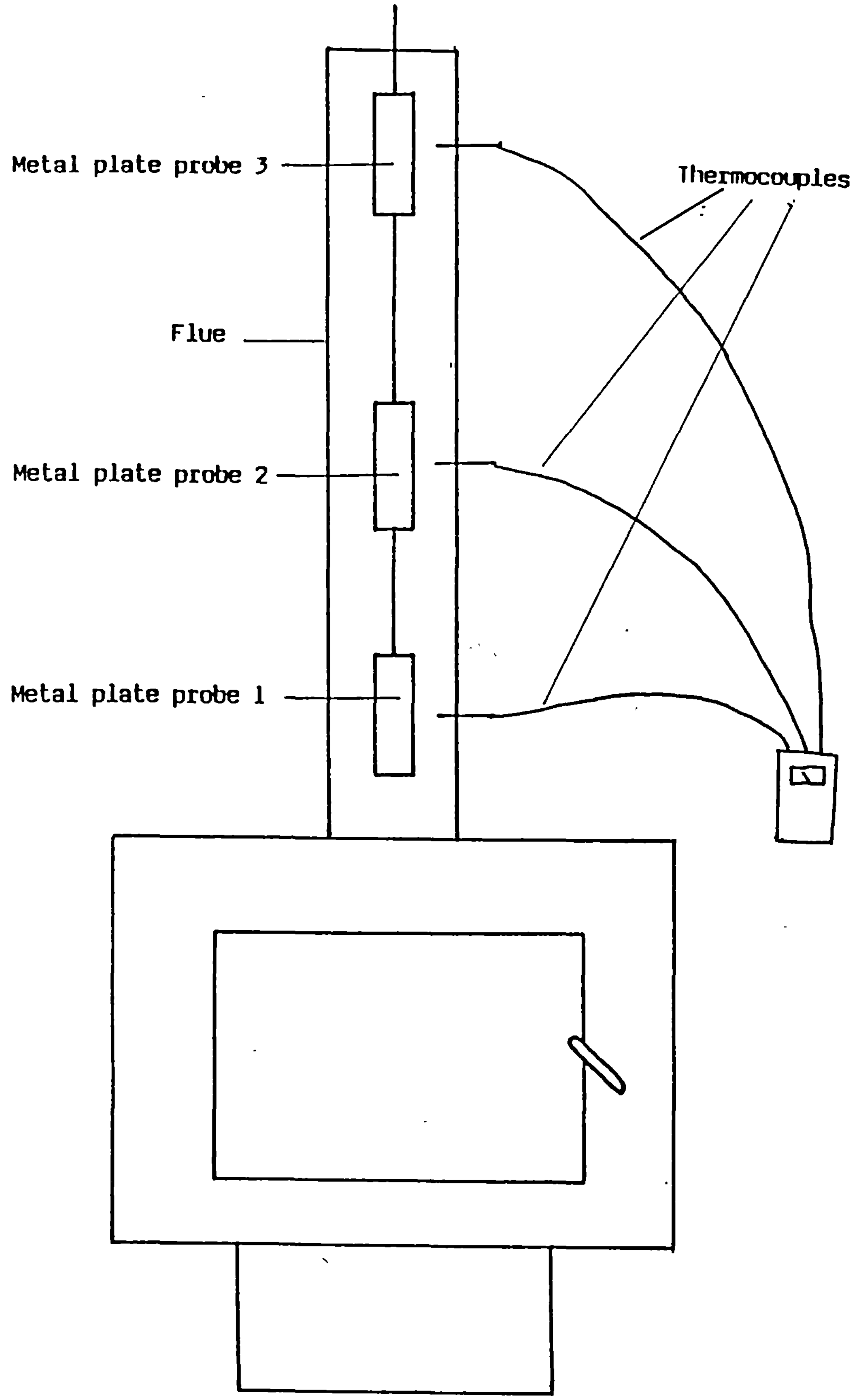


Figure 3.1. Diagram of creosote measuring apparatus

needed throughout the experiment. After 2 hours 10 minutes the probes were removed and weighed. Any unburnt fuel was also weighed.

3.1.2 Results and Discussion

Table 3.1 and 3.2 show the results for the seven wood tests and the four 50/50 fuel mix tests respectively. The creosote measurements are recorded as weight per unit area.

The results shown in Table 3.1 indicate that repeat tests give reasonably consistent results. Probe 1, which was located at the bottom of the flue, collected the least amount of creosote (16 units, average). This was most likely due to the higher flue gas temperature at this position. It appears that at 176 degrees C little condensation of creosote occurs. Inspection of probe 1 after the tests revealed a light brown powder covering which was probably soot and other particles carried up by the exiting air flow.

TABLE 3.1

Creosote measurements and Probe Temperatures (degrees C) for 100% Wood.

TEST	PROBE CREOSOTE (mg/sq cm) 1	2	3	PROBE TEMPERATURE (degrees C) 1	2	3
1	.16	.75	.44	184	123	89
2	.10	.56	.40	168	121	89
3	.13	.82	.45	163	115	88
4	.21	1.05	.60	190	119	88
5	.22	.87	.57	184	119	89
6	.13	.55	.43	173	118	90
7	.14	.53	.49	171	118	89
average	.16	.73	.48	176	119	89
std.dev.	.04	.18	.07	9	2	1

average for all probes 0.456 mg/cm^2

TABLE 3.2

Creosote measurements and Probe Temperatures (degrees C) for 50/50 fuel mix

TEST	PROBE CREOSOTE (mg/sq cm) 1	2	3	PROBE TEMPERATURE (degrees C) 1	2	3
1	.26	.64	.47	165	113	89
2	.25	.90	.46	167	115	91
3	.17	.51	.46	179	119	92
4	.26	.70	.43	163	106	88
average	.24	.69	.46	169	113	90
std.dev.	.04	.14	.02	6	5	2

average for all probes 0.463 mg/cm^2

Probe 2 received the most creosote deposition (73 units, average). This was seen as a dark brown film which was very difficult to remove. The mean flue gas temperature at this position was 119 degrees C, apparently a much more favourable temperature than that at probe 1 for condensation.

Probe 3 gave a creosote value of 48 units for a flue gas temperature of 89 degrees C. At such a temperature one might have expected a higher value of creosote condensation. Such a result indicates the non-linear nature of deposition with regards to temperature. Possibly, by the time the gas has cooled to this temperature, most of the creosote has already condensed.

The results obtained from the tests using 50/50 wood/briquettes mix also show good repeatability (Table 3.2). The mean values obtained for creosote deposition on each probe relate closely to the corresponding values obtained using 100% wood. This pattern can also be extended to the mean temperatures for the tests.

These results suggest that, under the conditions followed in this investigation, there seems to be no significant change in creosote deposition when briquettes are introduced into the fuel load. The average weight of creosote collected on all three probes for wood and for wood/briquette mix are almost identical.
The reports from users may have resulted from the use of briquettes with wet wood. In such a case the presence of briquettes in the fuel load would most likely facilitate the combustion of wood volatiles which might otherwise escape up the flue. Even though there is no laboratory test evidence that confirms that wet wood produces more creosote than dry wood, further work in this area is recommended.

The values determined using the method of hanging steel plates in the flue cavity are most likley to be less than the actual quantity of creosote deposited on the inner surface of the flue. Using the plates in this manner would not be a direct representaion of the flue's inner surface. The plates would quickly reach the same temperature as the surrounding flue gases and so any creosote deposition would be related to the temperature of the gases passing the plate. This would not be the case with the flue metal since one side is continually exposed to the cooler room air. Such a temperature differential would result in a constant removal of heat from the inner surface and so promote condensation and deposition of creosote due to the inner flue surface being cooler than the passing gases.

One should also acknowledge that the results only relate to one particular heater and only one design. It would be expected that these results would differ from results obtained using other heater designs. Unfortunately, time restictions prevented further designs being tested. It was thought, however, that results obtained from emission and performance tests on other designs would give an indication of creosote deposition since these parameters of heater operation are closely linked. Since creosote is the result of smoke condensation in the flue, a heater with a high emission rate and low performance, would be more likely to deposite a greater quantity of creosote than a heater which performed well and had a lower emission rate.

3.2 Ash Weight Loss and Remaining Unburnt Fuel

The aim of these tests was to determine the amount of ash that is carried up the flue during the combustion process and to determine the particle size range of the char and ash that remains after the fire has been extinguished. Such information was important to know since emission measurements (section 3.3) could be effected if excessive amounts of ash were escaping up the flue.

3.2.1 Method

These tests were conducted in conjunction with efficiency tests on the Arrow 1800A woodheater. This particular heater is an updraught design with a cast iron grate and a cast iron lined firebox.

After completion of the efficiency cycles the fuel load was allowed to burn itself out and cool overnight. The cooled ash and unburnt coals were then collected and sieved through five size ranges, these being greater than 2mm, 2mm to 1mm, 1mm to 0.5mm, 0.5mm to 0.25mm, and less than 0.25mm. The weight of each seived sample was recorded.

A weighed representative sample from each size range was then placed in porcelain crucibles and heated to 600 degrees C in a muffle furnace for several hours in order to determine the relative quantities of ash and carbon in the material collected in the ash tray.

3.2.2 Results

A summary of results is shown in Table 3.3. The average burn rate for the three tests was 4.22 kg/h. Assuming a briquette ash content of 1.30%, every hour should result in an ash accumulation of 54.86 g. But the results show that an average of about 5% of the ash is lost up the flue. This can be represented as 2.78 g/h (average) of ash exiting the flue, with a range of 4.66 to 0.384 g/h. Also calculated was the percentage by weight of ash and char for each size range for each test run. This data is shown in Table 3.4.

TABLE 3.3

Summary of ash measurement results.

Test No.	Weight of Combusted Briquettes (g)	Expected Ash Weight (g)	Actual Ash Weight (g)	Percentage Ash Loss (%)
1	16226	211	193	8.5
2	21451	279	277	0.7
3	25457	331	311	6.05
			Average	5.08
		Standard deviation		3.26

TABLE 3.4

Percent by Weight of Ash and Char Remaining after Fire Has Gone Out as a Function of Ash and Char Piece Size.

Sieve Size (mm)	Test 1 %	Test 2 %	Test 3 %	Av. %	Standard Deviation
greater than 2	0	0	0	0	0
2 to 1	9.8	12.2	10.5	10.8	1.02
1 to 0.5	50.5	48.1	34.7	44.4	6.96
0.5 to 0.25	27.9	24.6	22.4	25.0	2.30
less than 0.25	11.8	15.1	32.4	19.8	8.99
	100.0	100.0	100.0	100.0	

3.2.3 Discussion

The results indicate that the quantity of ash that may be carried out of the heater by the flue gas with this particular heater under these operating conditions can vary significantly (0.7 to 8.5%). But even with the variation obtained, the amount of fly ash produced during combustion appears relatively small. The significance of this is discussed further in the following section dealing with emissions. It is interesting to note the regular pattern between the three tests regarding the distribution of ash and char particle size (Table 3.4). Such a distribution would affect the percentage of escaping ash since some would be retained in the larger particles.

The results also show the amount of fuel lost with the ash. The percentage loss for the first, second and third tests were 4.5, 3.1 and 2.4 respectively. These very limited tests suggest that very roughly 3% of the fuel is lost with this design of heater when operated in this way. This will contribute very slightly to reduced efficiency.

It should be noted that these test results are not necessarily applicable to other heaters due to different operating conditions and design factors.

Design factors such as the presence or absence of a grate and the depth of the area under the grate would effect the results. With heaters having a grate, as was the case in these tests, ash and small pieces of fuel would pass through the grate and away from the main combustion zone. In the Arrow heater tested, the ash tray is quite shallow and so the material falling into it remained close to the combustion zone. This would promote continued combustion of the fuel. In a heater with a deeper ash tray, fuel falling into it would be more likely to cool down and remain unburnt. Also, the removed ash would have little chance of escaping up the flue.

Heaters without a grate would give results indicative of the quantity of ash that would cover and insulate the fuel and how ferociously the fire was burning.

The ferocity, and hence the degree of air turbulance within the firebox, would also determine the quantity of ash escaping up the flue. This parameter would effect the quantities from all heater designs. Hence, operating conditions should also be considered.

3.3 Emissions

When firewood or briquettes are burnt in solid-fuel heaters combustion is not complete, the resulting smoke contains a large number of complex organic compounds and carbon monoxide. The nature of this smoke, particularly wood smoke, has been the subject of many studies in recent years; see, for example: De Angelis et al. (1980), Quraishi (1984) and U.S. Department of Energy (1980). The key features of heater smoke which have relevance to this report are:

the smoke contains many compounds which are known carcinogens or precursors of respiratory problems,

many of these compounds are formed as gases and then condense in the flue or the atmosphere,

the condensed particles are very small (less than 5 microns diameter) and so are in the respirable particle size range (Quraishi 1985).

In view of these features it seems very likely that some control of this source of atmospheric pollution will be introduced in Australia in coming years.

Getting representative measurements of emissions from solid-fuel heaters is not a straightforward matter. There is the problem of collecting condensed particles (gases must be cooled before filtering), the problem of non-uniformity of fuels, and the problem of varying operating procedures of the heater during tests. Several methods have been used for measuring heater emissions but, unfortunately, different methods give different results.

One method which has gained fairly widespread acceptance by research groups is the dilution tunnel method. The dilution tunnel method is detailed in the report by Todd, Quraishi and King (1988). The basic principle of the method is as follows:

(i) A heater is operated in a test laboratory in a prescribed fashion using a prescribed fuel. The fuel must be standard in order to give emission results which are reproducible; this means specifying the moisture content, individual piece size, the geometry and the total weight of the fuel load. A load of fuel is then burnt in the heater under various operating modes.

(ii) The height and insulation of the flue used with the heater are specified. Scales are used under the heater to determine the weight of fuel burnt.

(iii) All the smoke from the top of the flue is collected by a hood which dilutes the smoke with a considerable volume of clean air. The reason for this dilution is to cool the smoke so that volatiles will condense. The diluted and cooled smoke is drawn through the dilution tunnel which allows time for complete mixing.

(iv) A sample of the diluted smoke is drawn out of the tunnel and passed through filters to collect all particulates in the sample. The mass of particulates is accurately measured.

(v) From measured mass flow rates in the dilution tunnel and in the sample train the total mass of particulates emitted by the heater over a full cycle can be calculated. This emission can then be related to the mass of fuel burnt (grams of particulates per kilogram of fuel burnt (g/kg)) or to the average rate at which particulates are emitted (grams of particulates per hour of heater operation (g/h)).

See Figures 3.2 and 3.3

3.3.1 Method

Two heater designs were tested for emissions using different combinations of wood and briquettes, these being the Arrow 1800A and the Heatcharm. The Arrow is an updraft design where air enters the firebox under a grate, passes directly through the grate upon which

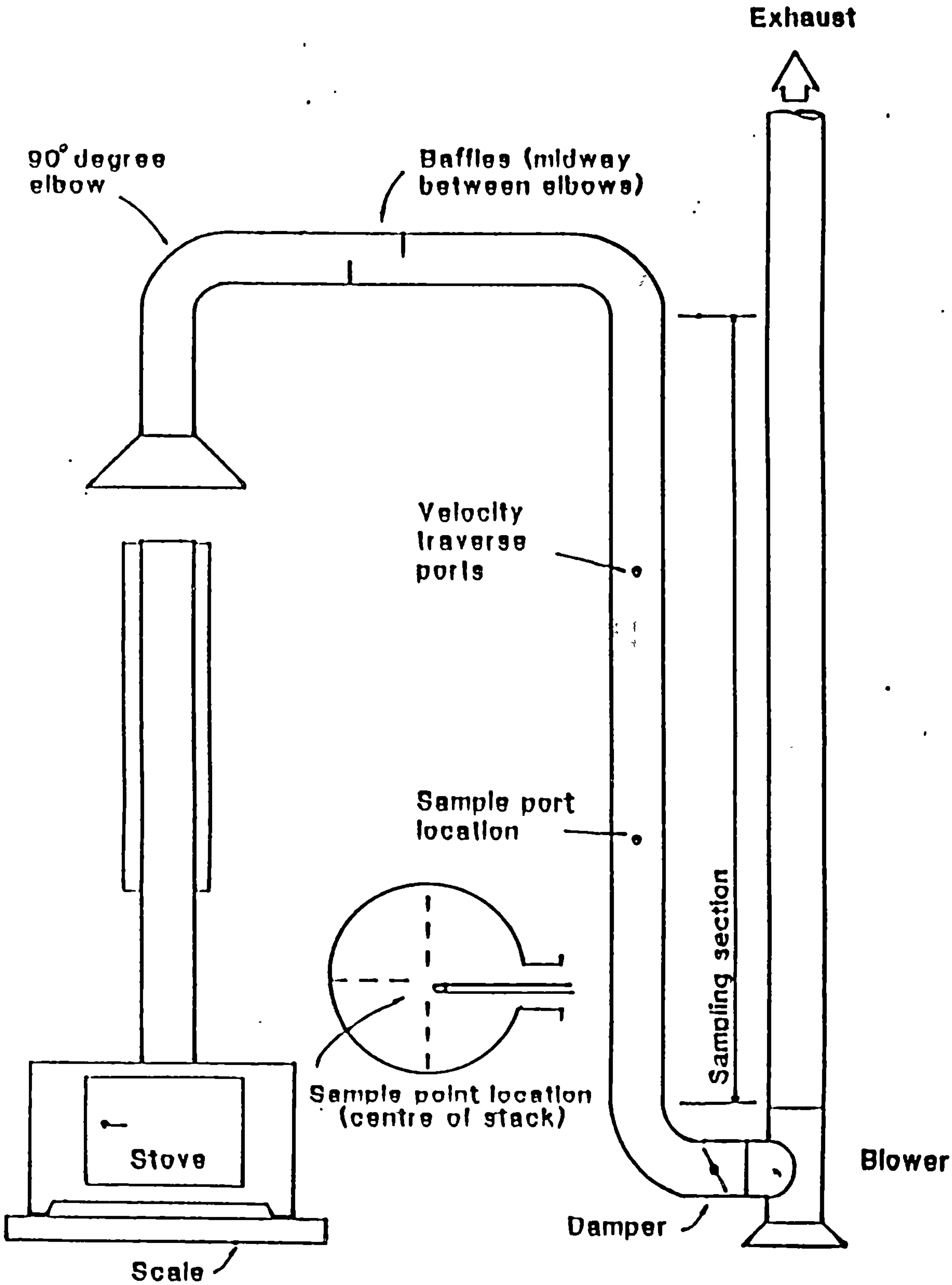


Figure 3.2. Diagram of the dilution tunnel at the Home Heating Laboratory (TODD, QURAISHI and KING 1988).

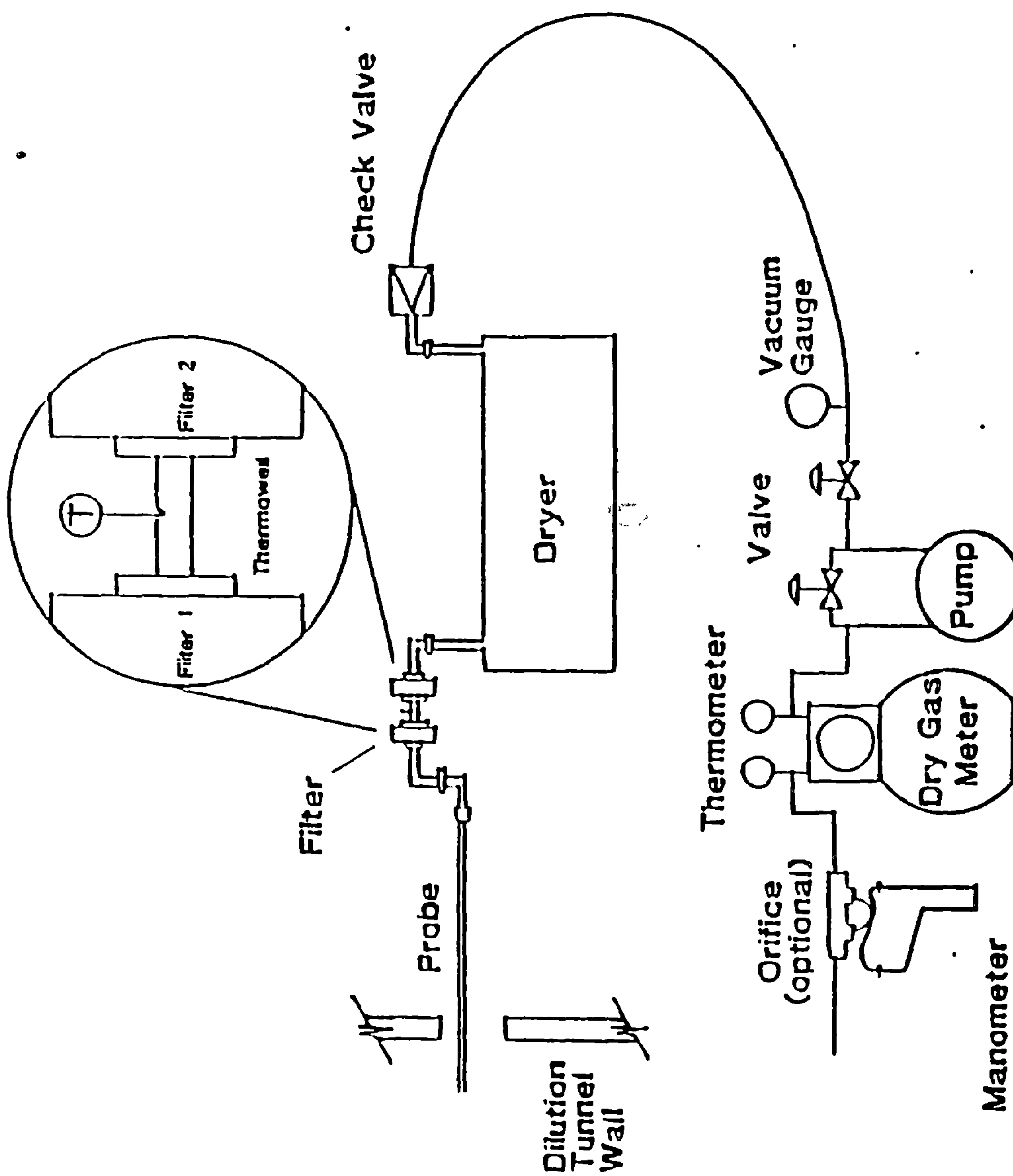


Figure 3.3. Method 5G sampling train (TODD, QURAISHI and KING 1988).

the fuel is burnt and exits at the top of the firebox via the flue (see Section 4.4 for full specifications).

The Heatcharm is an 'S'-draft design with no grate. Hence the fuel lies directly upon the firebox base (see Section 4.4 for full specifications). However, a set of tests was conducted using the Heatcharm whereby a grate was made from 5mm steel plate and placed in the firebox and raised with small bricks by about 50mm from the firebox base. This modification enabled a direct comparison of results to be made between burning fuel on a flat firebox base and burning on a grate while keeping all other variables constant. Testing was done in conjunction with efficiency tests in the calorimetry room (see Chapter 4). The method involved igniting the heater with either briquettes or eucalyptus firewood and conducting warm-up cycles to allow the heater and calorimetry room to reach thermal equilibrium. Once the warm-up cycles had been completed, the heater emissions were tested with either eucalyptus firewood or briquettes at a particular air intake and convection fan setting.

3.3.2 Results and Discussion

Table 3.5 gives details of heater control settings, performance and emission for the series of five tests conducted on the Arrow 1800. On average, the emission rate when burning briquettes was 36 g/h, while with wood it was 11 g/h. Table 3.6 gives the average results obtained on the Heatcharm C500.

TABLE 3.5

Summary of data from emission tests on the Arrow 1800A heater when fuelled with eucalyptus and briquettes on the maximum heat setting.

FUEL	No. TESTS	AVERAGE EMISSIONS g/h	AVERAGE EFFICIENCY %
100B	3	36	54
100W	2	11	59

100B = 100% Briquettes
100W = 100% Wood

TABLE 3.6

Summary of data from emmision tests on the Heatcharm heater when fuelled with eucalyptus and briquettes on the maximum heat setting.

FUEL	No. TESTS	GRATE	AVERAGE EMISSION g/h	AVERAGE EFFICIENCY %
100B	3	YES	4.99	58
100B	2	NO	32.22	45
100W	20	NO	4.00	51
50 B	2	NO	5.06	57

100B = 100% Briquettes
100W = 100% Wood
50B = 50% Briquettes and 50% Wood

Heatcharm

The results show that the tests conducted with 100% briquettes with the addition of a grate were remarkably different from the results obtained when no grate was present. Use of the grate appeared to reduce emissions by a factor of 6.

These results and visual observations indicate increased air circulation in and around the fuel when the grate was present. The volatiles released from the heated fuel were kept close to the combustion zone and so increasing the chance of complete combustion. The absence of a grate meant that the combustion air was not able to circulate as effectively in and around the fuel so as the air left the firebox it carried away a large quantity of unburnt volatiles, hence the greater emissions.

The 50/50 fuel mix emission result was comparable to the 100% briquettes plus grate result. The presence of the wood (being placed in and around the briquettes) probably acted to reduce briquette emissions in two ways . Firstly, the geometry of the wood would act much like a grate, allowing combustion air to circulate within the fuel load and, secondly, the burning wood would also assist in igniting the briquette volatiles. Having no briquettes in the fuel load resulted in the lowest recorded emissions

Arrow 1800A

The results obtained from the Arrow show a similar trend in emissions to the Heatcharm; 100% briquettes giving the larger result. However, the Arrow results are greater. Being a grated heater one would have expected the results to be much less and more comparable to the Heatcharm results especially the result obtained using a grate with 100% briquettes. The major difference between the Arrow and the Heatcharm plus grate is the way in which the combustion air is introduced into the firebox. With the Arrow being an updraft design the combustion air travelling up through the fuel bed would exit the firebox via the flue without much opportunity for ciculation around the combustion zone. The result being that volatiles would be removed from the combustion zone with little chance of complete combustion.

The results for the two heaters tested indicate that air flow in and around the burning fuel is required and also the time the combustion air spends in the zone should be as long as possible in order to minimise emissions. Hence, sufficient air is needed, but not in such a way as to carry unburnt volatiles away from the combustion zone.

While these conclusions are only drawn from a few tests on two heater designs the trend to high emissions with briquettes is evident and this area will need attention in future especially if emission controls are introduced into Australia.

With this being a strong possibility it is instructive to compare them with the recently introduced limits set for emissions from wood burning heaters in the United States (Environment Protection Agency 1988). The US limits are based on a weighted average of emission rates at four different burn rates (the results reported here are for a single burn rate only). The fuel used in the US testing is dressed timber nailed into a grid of fixed geometry, whereas these tests used either briquettes or split firewood. The US legislation does not apply to coal burning heaters. Thus, there are many differences in procedure which add to the need for caution in making comparisons. Table 3.7 lists the emission limits which must not be exceeded by any heater manufactured after the dates shown for Phase 1 and Phase 2 of the legislation. The emission rates in these tests, when burning firewood were close to the highest emission rate shown in Table 3.7, but the emission rates when briquettes were burned in the Arrow and unmodified Heatcharm were about 4 times the limit.

Table 3.7

Woodheater emission limits set by the United States Environment Protection Agency.

Type of heater	Phase 1 (heaters manufactured after 1/7/88)	Phase 2 (heaters manufactured after 1/7/90)
Catalytic heater	5.5 g/h	4.1 g/h
Non-catalytic heater	8.5 g/h	7.5 g/h

One important aspect of the control of emissions from heaters burning wood is the nature of the emission (as previously mentioned). The chemical composition and size of the emissions when briquettes are burnt are not known. It is probable that there will be many substances in the emission similar to those in wood smoke but there may be a significant ash component as well. Ash may be less of a health hazard than the condensed volatiles making up the bulk of wood smoke emissions. The ash measurements, discussed in Section 3.2, suggest about 3 g/h of ash carry-over, or only about 10% of the mass emission rate. At this stage, all that can be concluded is that further analysis and quantificaton of emissions seems advisable.

Improved firebox design or, possibly, catalysts offer ways of reducing emissions from heaters burning briquettes. Catalysts are used to reduce emissions from wood burning heaters, but some types of catalyst will deteriorate rapidly if chlorine or sulphur are present in the fuel and are not recommended for use with coal. Catalysts are available for coal burning appliances and these may have some application in briquette burning heaters. But all catalysts require periodic replacement and it seems preferable to achieve clean burning through good design of the combustion chamber rather than opting for a catalyst.

Another point that should be mentioned regarding emission testing is that the tests are conducted under strict labroratory conditions and there is much conjecture that such procedures do not relate to what happens under real world conditions. A particular heater which may produce low emission levels under laboratory conditions does not repeat the results when operated by consumers. Studies comparing laboratory emission results with real world levels showed much higher emissions with the latter (Wood 'n Energy, Feb.1988). So not only do manufacturers have to design low emission heaters but also user education in heater operation must play a large part in reducing heater emissions. This subject and other related factors is reported in detail by Todd and Singline (1989) in their study on "The Impact of Woodheaters on Air Quality in Australia".

4 PERFORMANCE

A major part of this project was to establish how well various designs of heater performed when fuelled with briquettes and briquette/wood mixes compared with their performance when fuelled with firewood. The efficiency and power of an appliance are commonly used as indicators of performance. The length of time a single fuel load will burn unattended is another useful indicator.

Performance testing was carried out in the calorimetry room in the Home Heating Laboratory. The facility was briefly described in Section 1.2.2. The test method and procedures followed were those specified in 'Draft Test Method for Performance Rating of Woodheaters' (Todd and Sawyer 1987).

4.1 Power

All power and efficiency measurements are based on the combustion of a complete load of fuel. The size of the fuel load is determined by the volume of the combustion chamber of the heater (0.1 kg per litre of combustion chamber). For the tests reported here the fuel load was 3.5 to 4.5 kg. This fuel load is added to a burning bed of charcoal weighing about 2 kg. The fuel load is considered to have completely burnt when the total fuel weight returns to the initial charcoal weight.

The power, or heat output rate, of the heater is measured at two minute intervals. This is averaged over the burn cycle to give an average power for a particular setting of the combustion air control.

4.2 Efficiency

The efficiency of a residential solid fuel heating appliance depends on how completely the fuel is burnt (combustion efficiency) and how completely the heat released during combustion is transferred into the living space (heat transfer efficiency).

Combustion efficiency is defined as the fraction of the gross calorific value of the fuel released as heat during the combustion of the fuel. The combustion efficiency can be reduced by unburnt fuel escaping in the flue gas (either in solid or gaseous form) or by unburnt fuel remaining in the ash and being removed when ash is removed.

Heat transfer efficiency is defined as the fraction of the heat released during combustion which is transferred to the space to be heated (living area). Heat transfer losses are all associated with losses out the flue. They are a combination of sensible heat loss due to the elevated temperature of the flue gases and latent heat loss due to water vapour and any other gases which would condense at room temperature.

The overall efficiency of a solid-fuel burning heater is the product of the combustion efficiency and the heat transfer efficiency. It is the fraction of the gross calorific value of the fuel burnt which is transferred as useful heat into the space to be heated.
The overall efficiency is usually just referred to as the efficiency. Thus,

$$\text{Efficiency (\%)} = \frac{\text{useful heat output}}{\text{calorific value of fuel}} \times 100$$

The efficiency is calculated by integrating the measured power over a full burn cycle to give the energy output and dividing this by the energy content of the fuel used for the burn cycle.

If comparisons of efficiency measurements are being made it is important to establish whether like is being compared with like. That is, whether combustion efficiency or overall efficiency are reported and whether efficiencies are expressed relative to the gross energy content of the fuel (referred to as high heat value in some US literature) or relative to the net energy content of the fuel (low heat value). (The net heat value of a fuel deducts the latent heat of water vapour in the combustion products but its use can lead to confusion and is not used in Australian work on woodheaters.)

4.3 Burn Time

The burn time is merely the time taken to burn a single fuel load. One important selling point of modern heaters is their ability to 'burn overnight'. To test this a larger fuel load than used for power and efficiency testing is placed in the heater (0.2 kg per litre of combustion chamber). The heater is considered to have achieved overnight combustion if a load of kindling will ignite 8 hours after the heater is turned down to the low or overnight combustion air control setting. The heater is run with the air control fully open until 25% of the weight of the fuel load is burnt and only then turned down to the slow burning setting.

4.4 Appliances Tested

Three domestic solid-fuel burning appliances were tested with a combination of fuels. The heaters tested were:

(i) Arrow 1800A. This heater has a useable firebox volume of 42 litres. The firebox consists of a cast iron grate which is raised off the firebox floor. The firebox is lined with cast iron plate which extends 200 mm above the grate. There is a horizontal baffle in the upper section of the firebox. The space below the grate contains the ash removal tray. Access to this tray is via a door which also contains the combustion air inlet holes to allow air to enter the firebox below the grate. The heater is a convection design and includes a three speed fan to aid convection.

(ii) Stack Vista 640. This heater also has a grate with underfire air but includes an uncontrolled, preheated secondary combustion air supply entering above the fuel (directed down the inside of the glass panel in the door). Within the firebox there are side and rear wall cast iron mouldings which extend up to and support the cast iron baffle. The heater has a useable firebox volume of 37 litres. On the base of the firebox is a rabbling grate and below the grate is the ash tray housing. Combustion air enters at the rear of the ash tray compartment. Testing of this appliance revealed the presence of air leaks around the firebox. This reduced the control of the burn rate and test precision.

(iii) Heatcharm C500. This heater has no grate and is an 'S' draft design. The firebox has a usable volume of 38 litres. The rear and side walls of the firebox have a 10mm thick cast iron lining and the base is covered with 20mm thick firebricks. The combustion air intake control is a swinging metal flap which controls air intake through four slots situated at the top front of the firebox to create a down wash or 'S' draft air flow. There are also two secondary air intakes, however, these were blocked off for all tests done on the heater. The heater is also a fan assisted convection heater, but the fan was not used for any of the tests.
Several tests were conducted with the use of a home made grate. This grate was made from 5mm steel plate and had six slots of 300mm length and 15mm width running parallel to the heater door.The grate was held up with small firebricks to a height of 50mm. The sides and rear of the grate were flush with the walls of the firebox leaving a 30mm gap at the front.

4.5 Test Procedures

4.5.1 Fuel Characteristics

Wood: The weight, size, shape and fuel load was determined by the method described by Todd and Sawyer (1987). This involved tailoring commercially bought Eucalyptus firewood. The fuel load was kept at approximately 0.1 kg per litre of usable firebox volume.

Briquettes: This fuel was used as delivered. The fuel load weight was the same as that used for wood.

Fuel Energy Content: For Eucalyptus the gross calorific value used was 19.6 MJ/kg for oven dry wood. The calorific value of the wood as fired was calculated for each load using the average moisture content of the fuel load. The average value was 15.9 MJ/kg (gross). The calorific value assumed for briquettes was 22.53 MJ/kg (gross) as fired.

4.5.2 Fire Ignition

High burn rate: For all fuel mixes the fire was ignited by placing 5 to 6 kg of the fuel mix directly onto the base of the firebox and igniting 1 to 1.5 kg of kindling and crumpled newspaper on top. When wood was part or all of the fuel the ignition load was made up of scrap wood. Burning of this first fuel load (cycle 1) was considered complete when the weight had reduced to about 2.00 kg. At this point, cycle 2 commenced. Cycle 2 was considered complete when the fuel weight had returned to that before loading.

Medium and low burn rate: The method of ignition was the same as that described for the high setting. But when 25% of the fuel load had been consumed the air inlet was adjusted to the medium or low setting for the remainder of the cycle. The next cycle was commenced when a weight of about 2 kg was reached.

4.5.3 Warm-up Cycle(s)

The point at which the warm-up cycles ended and the test cycles began was calculated after testing was complete and results calculated. The completion of the warm-up cycle/s was determined by the following procedure:

(i). The peak and end power of the final warm-up cycle should be within 20% of the respective average of peak and end powers of the following cycles.

(ii). If this is the case, then the next cycle marks the beginning of the test cycles.

(iii). If this is not the case then the same calculation is carried out on the next cycle and so on, until the requirements are met.

4.6 Performance Results

A total of 125 fuel loads were burnt in the Arrow 1800 heater as part of the performance testing, of which 74 met the criteria for repeatability set out in the test method (51 of the burn cycles were warm-up cycles). A further 63 fuel loads were burnt in the Stack Vista 640 heater, of which 29 met the repeatability criteria. The erratic burning observed with the Stack heater led to the higher proportion of cycles rejected as valid test results. A total of about 70 fuel loads were burnt in the Heatcharm C500 of which 38 met the repeatability criteria.

The full results, including observed performance for each individual load of fuel burnt, are contained in five reports prepared for the Coal Corporation of Victoria (Todd and Wingham 1987b, 1987c, 1988a, 1988b, 1988c). The results are summarised in Tables 4.1 and 4.2. Table 4.1 shows the average efficiency and power for each heater when fuelled with either briquettes, wood or a mix of briquettes and wood at various combustion air settings. Table 4.2 shows the average fuel consumption rate and time taken to burn a load of fuel for the same set of variables as Table 4.1.

TABLE 4.1

Summary of efficiency and average power results for tests on the Arrow 1800A Stack Vista and Heatcharm C500 heaters. The numbers in brackets in the efficiency and power columns represent one standard deviation of the efficiency and power measurements.

OPERATION	FUEL *	NUMBER OF TESTS	EFFICIENCY %	AVERAGE POWER kW
ARROW 1800A				
HIGH NO FAN	100B	7	49.1 (2.2)	13.9 (0.6)
	100W	9	49.2 (4.4)	14.7 (0.7)
HIGH FAN ON	100B	7	55.0 (3.8)	14.3 (0.5)
	50 B	7	51.7 (2.9)	15.8 (0.4)
	25 B	4	51.5 (2.6)	15.7 (0.3)
	100W	7	49.1 (3.6)	14.8 (0.7)
MEDIUM FAN ON	100B	6	61.0 (1.8)	8.3 (0.7)
	50 B	3	60.7 (2.1)	10.2 (0.8)
	25 B	3	58.8 (2.4)	10.9 (0.4)
	100W	7	56.0 (1.8)	11.1 (0.4)
LOW FAN ON	100B	3	67.2 (0.9)	5.4 (0.3)
	50 B	1	64.4 -	5.3 -
	25 B	2	62.8 (1.5)	6.2 (0.1)
	100W	3	58.1 (2.9)	7.1 (0.3)
STACK VISTA				
HIGH	100B	4	48.0 (2.0)	14.1 (0.3)
	50 B	6	52.5 (3.3)	14.7 (0.8)
	25 B	4	48.8 (5.2)	15.5 (0.5)
	100W	4	49.5 (2.6)	16.3 (0.3)
LOW	100B	5	53.2 (3.3)	9.7 (0.3)
	50 B	2	57.5 (2.5)	7.5 (0.3)
	100W	4	50.5 (2.7)	10.8 (0.7)
HEATCHARM C500				
HIGH WITH GRATE	100B	10	56.0 (4.5)	15.7 (1.9)
HIGH NO GRATE	100B	3	48.0 (5.7)	5.7 (0.9)
	50 B	5	55.0 (1.5)	8.9 (0.8)
	100W	20	51.0 (3.1)	13.1 (1.0)

* 100B = 100% briquette fuel,
50B = 50% briquette 50% wood fuel,
25B = 25% briquette 75% wood fuel,
100W = 100% wood fuel.

TABLE 4.2

Summary of burn rates and cycle times for tests on the Arrow 1800A, Stack Vista and Heatcharm C500 heaters. The figures in brackets in the burn rate and cycle time columns represent the standard deviation of the burn rate and cycle time measurements.

ARROW 1800A

OPERATION	FUEL *	NUMBER OF TESTS	BURN RATE kg/h	CYCLE TIME min
HIGH NO FAN	100B	7	4.57 (0.30)	56 (5)
	100W	9	6.89 (0.70)	37 (4)
HIGH FAN ON	100B	7	4.19 (0.39)	61 (6)
	50 B	7	5.65 (0.33)	49 (4)
	25 B	4	6.00 (0.31)	42 (1)
	100W	7	6.89 (0.24)	38 (3)
MEDIUM FAN ON	100B	6	2.17 (0.27)	124 (15)
	50 B	3	2.89 (0.15)	97 (11)
	25 B	3	3.67 (0.07)	72 (0)
	100W	7	4.24 (0.17)	65 (4)
LOW FAN ON	100B	3	1.27 (0.07)	191 (4)
	50 B	1	1.50 -	160 -
	25 B	2	1.97 (0.07)	127 (1)
	100W	3	2.62 (0.04)	101 (7)

STACK VISTA

OPERATION	FUEL *	NUMBER OF TESTS	BURN RATE kg/h	CYCLE TIME min
HIGH	100B	4	4.71 (0.19)	46 (2)
	50 B	6	5.09 (0.51)	47 (4)
	25 B	4	6.25 (0.55)	37 (3)
	100W	4	7.03 (0.36)	29 (2)
LOW	100B	5	2.93 (0.24)	75 (7)
	50 B	2	2.39 (0.00)	95 (1)
	100W	4	4.58 (0.49)	48 (6)

HEATCHARM C500

OPERATION	FUEL *	NUMBER OF TESTS	BURN RATE kg/h	CYCLE TIME min
HIGH WITH GRATE	100B	10	4.68 (0.52)	74
HIGH NO GRATE	100B	3	1.88 (0.16)	>185
	50 B	5	3.02 (0.35)	115
	100W	20	4.62 (0.41)	-

* 100B = 100% briquette fuel,
50B = 50% briquette 50% wood fuel (by weight),
25B = 25% briquette 75% wood fuel (by weight),
100W = 100% wood fuel.

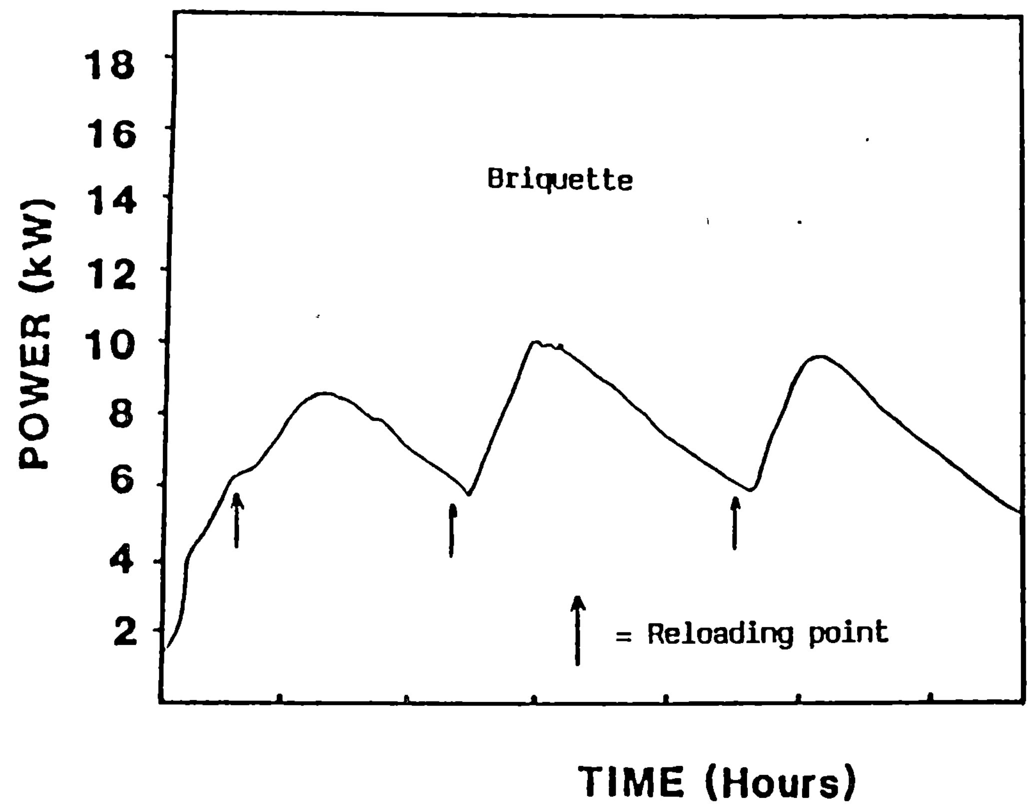
The differences in the nature of the burning cycles of briquettes and wood are illustrated in Figure 4.1. It can be seen that the briquette fuel leads to a more regular and longer burn cycle. The briquette fuel also has a greater range of power for a single burn cycle than the wood. The irregular power curve for the wood fuel is caused, in part, by the collapse of the wood stacked in the heater which usually leads to more rapid burning for a short period.

4.7 Overnight Burn Test Results

Another important performance feature of a solid-fuel heater is its ability to burn overnight on a single fuel load. The test used to determine whether or not a heater can burn overnight (eight hours) is different in concept from the efficiency tests. The fundamental difference is that it is a test to see if the heater will burn for a fixed time rather than measuring the time required to burn a fixed fuel load.

The overnight test commences in the same manner as the other tests with respect to lighting and warm-up cycles. The fuel load used is double that used for efficiency tests (0.2 kg per litre of fuel chamber volume). The fuel is added to an established bed of burning coals and the heater run on its high burn rate setting until 25% of the weight of the fuel load is burnt. The controls are then adjusted for overnight burn. Eight hours after setting the controls to the overnight burn positions the appliance is checked to see if it is still alight. If there is any doubt about this, it is resolved by refuelling the appliance with eucalypt kindling and opening the air intake fully. If the fuel ignites after 10 minutes the appliance can be considered to have sustained overnight burning.

Due to the high burn rate of the Stack Vista heater on its lowest setting, overnight burn tests were not conducted with this heater. Overnight tests were not conducted on the Heatcharm.



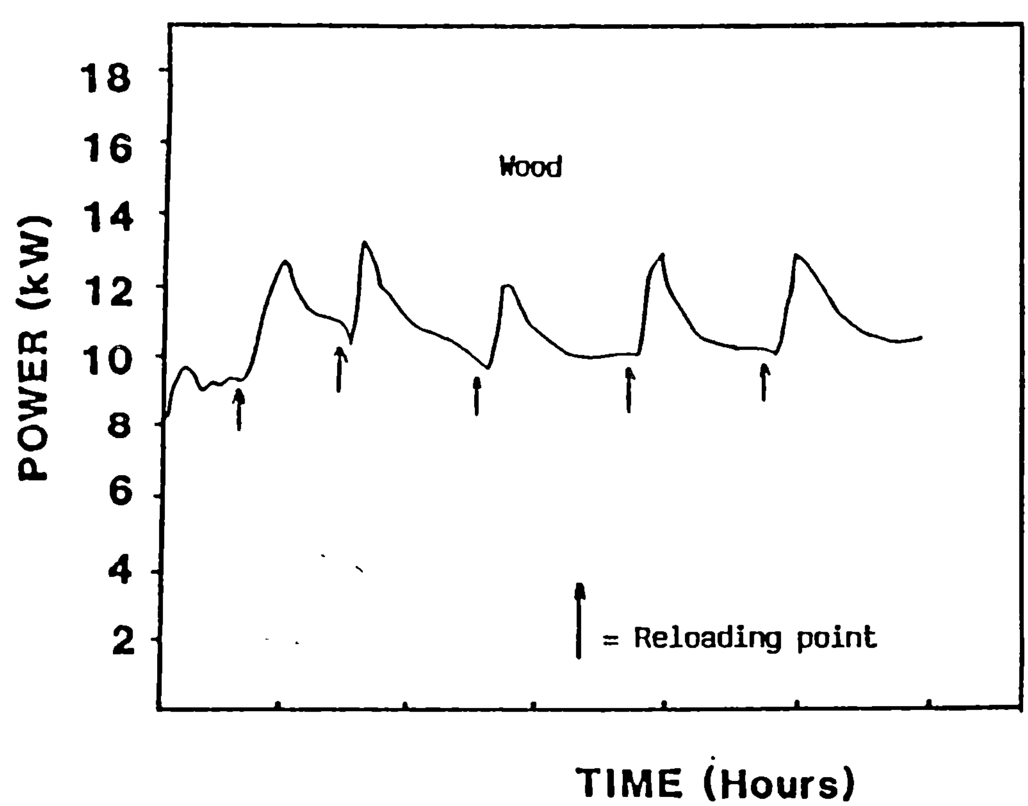


Figure 4.1 Typical burn cycles for briquettes and wood (Arrow 1800A at medium burn rate).

Two tests were conducted using wood in the Arrow 1800A heater, one using briquettes, one using a 50/50 mix of wood and briquettes and one on a 75/25 mix (25% briquettes).

Table 4.3 summarises the tests. The result of passed or failed refers to whether or not the heater burnt overnight.

TABLE 4.3

Test results for the overnight burns using 100% wood, 100% briquettes, 75% wood, and 50% wood on the Arrow 1800A with no fan.

TEST	FUEL	RESULT	FLUE TEMPERATURE AT END OF TEST (degrees C)
1	Eucalyptus	Failed	50
2	Eucalyptus	Failed	56
3	Briquettes	Passed	142
4	50/50	Passed	120
5	75/25	Passed	94

The addition of briquettes to the fuel for an overnight burn greatly affected the overnight performance as indicated by the results. Every fuel load which contained briquettes passed the overnight test whereas the all wood loads did not.

The flue temperatures at the end of the eight hour time period indicated the effect of briquette addition on the length of burn time. The higher the temperature the more vigorously the fire was still burning at the end of the test period.

4.8 Discussion of Performance Results

4.8.1 Arrow Heater

(i) On all settings, except with the fan off (see (ii) below), there is a trend to higher efficiencies when briquettes are burnt in the Arrow 1800A appliance. This improvement in efficiency increases with an increased briquette percentage in the fuel load. The reason for this is not obvious but it may be because the higher volatile content of wood means more flame and more chemical energy released as the burning gas nears the flue exit. This might result in more sensible heat loss up the flue. Figure 4.2 shows the flue temperature as a function of power during various stages of several burn cycles (for the Arrow heater on high burn rate with the fan on). The 'tail', or char burning phase, of the burn cycle is much more apparent with briquettes than with wood. During this phase, flue temperatures are significantly lower for an equivalent power indicating better heat transfer efficiency.

(ii) For the Arrow heater, the efficiencies of 100% wood and 100% briquettes were about the same when the fan was not operating. Both fuels resulted in a 49% measured efficiency. This is not a particularly good efficiency for a controlled combustion heater. These efficiencies were the same as the results obtained for the 100% wood burn on high setting with the fan operating. This result seems a little surprising because the design of the heater is such that natural convection is quite constricted because of the shape of the outer casing of the heater. Forced convection air should improve the heat transfer efficiency in such cases. But the result is consistent with other measurements of wood fuelled free standing heaters which show little improvement in efficiency when fitted with a convection fan. It may be that the increased heat transfer efficiency gained by fan operation is offset by a reduction in combustion efficiency due to cooler firebox temperatures.

Another observation is that the average power outputs for the 'fan off' and 'fan on' test using 100% briquettes were quite similar (13.9 and 14.3 kW respectively), yet the fan off condition resulted in a higher burn rate and a 6% decrease in efficiency compared to the fan on results. This suggests a greater sensitivity to firebox conditions for briquettes. The operation of the fan would result in additional heat being extracted from the fire box. This heat extraction seems to favour the combustion of briquettes by cooling the firebox and extending the burn time without reducing combustion efficiency at the same power output.

If the average flue temperatures over a cycle are compared, as shown

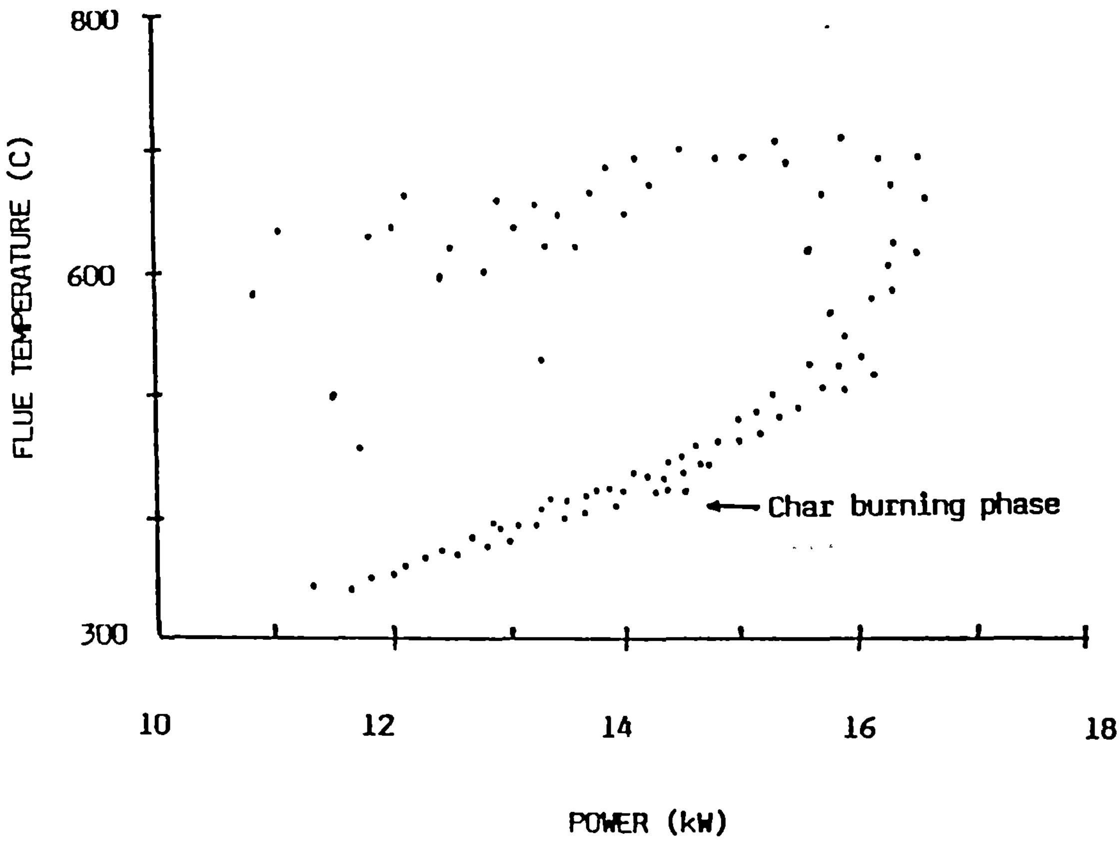


Figure 4.2. Flue temperature as a function of power output for several burn cycles with 100% briquettes in the Arrow (high burn rate with fan operating).

in Table 4.4, the sensitivity of briquette combustion to firebox temperature is indicated by the significant lowering of the flue gas temperature when the convection fan is on. Flue gas temperatures for wood combustion are not affected to such a degree.

TABLE 4.4

Average flue gas temperature measured 500 mm above the top of the heater for tests on high burn rate with the fan on and off.

	Average Flue Temperatures (degrees C)	
	Briquettes	Wood
FAN ON	497	573
FAN OFF	585	600
DIFFERENCE	88	27

The proximate analysis of both fuels shows a significant difference in the percentage of volatiles and fixed carbon present (Table 1.1). Briquettes have about 44% volatiles and 42% fixed carbon, whereas wood has 70% volatiles and 15% fixed carbon. In the case of briquettes this might partly explain the longer burn times and more pronounced char burning tail that is observed, since the larger amount of fixed carbon would burn as char giving a slower and more evenly burning fuel. The larger amount of volatiles in wood might explain the higher flue temperatures. But there are other factors which would contribute to these observations such as size, density and shape of the fuels used.

(iii) For the 'fan on' tests in the Arrow, the efficiency figures indicate that the presence of wood is not nesessary for good briquette combustion. It was thought that the wood might have made the briquettes burn faster because of better air infiltration. The slightly higher power figures for the wood/briquette mix suggest this may be the case. It is likely that the combustion efficiency, rather than the heat transfer efficiency, increases due to wood addition. This was indicated by a reduction in emissions (see section 3.3)

(iv) The efficiency for all fuel mixes increased as the combustion air was decreased. This suggests that at high burn rates the heat transfer efficiency is the limiting factor.

The increase in efficiency in going from high to low burn rates was 12.2% for 100% briquettes (22% increase over the high burn efficiency) and 9.04% for wood (18.4% increase over the high burn efficiency). A similar analysis on the burn rates and power output shows that for 100% briquettes the burn rate and power output decreased by 2.92 kg/h and 8.87 kW respectively (or a 70% and 62% decrease respectively). For 100% wood the burn rate and power output decreased by 4.27 kg/h and 7.69 kW respectively (or a 62% and 52% decrease respectively). The average power for medium and low are a function of air intake setting. These tests were all done at the same settings, but, of course, the air intake settings could be adjusted so that the power would be the same irrespective of what fuel mix was used.

The relative improvement in efficiency as the power decreases appears to be roughly the same for wood as for briquettes as illustrated in Figure 4.3.

(v) The cycle time, or time required to burn one load of fuel completely, was significantly greater for briquettes than for wood. Figure 4.4 shows the cycle times for the Arrow heater when fuelled with different proportions of briquettes. The cycle time with 100% briquette fuel is 60% longer than with wood. As the proportion of briquettes increases the cycle time appears to increase almost linearly.

(vi) The overnight burn capability of the Arrow heater was significantly improved by the addition of some briquettes to the fuel load. When the fuel load was only wood the heater failed the overnight burn test. When briquettes were added to the fuel it passed. It should be noted here that this does not mean that this heater is incapable of burning overnight on wood fuel because it would be possible to fit a larger fuel load into the firebox or adjust the air control more carefully to get just the right air supply for sustaining the minimum combustion rate. But the overnight burn test has been developed to assess whether or not a heater will readily burn unattended for 8 hours or more, and these

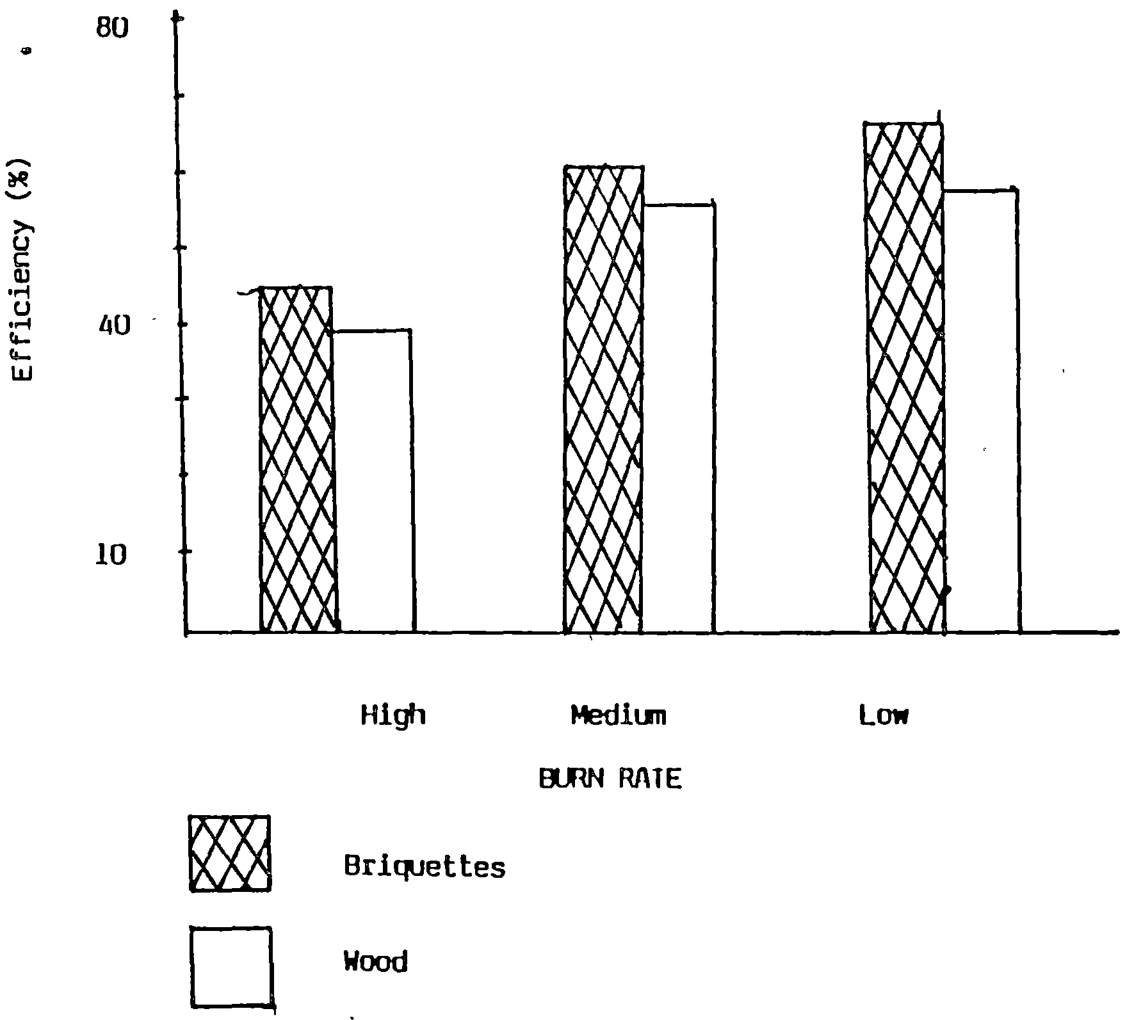


Figure 4.3. Comparison of overall efficiency for briquettes and wood at different burn rates in the Arrow 1800A.

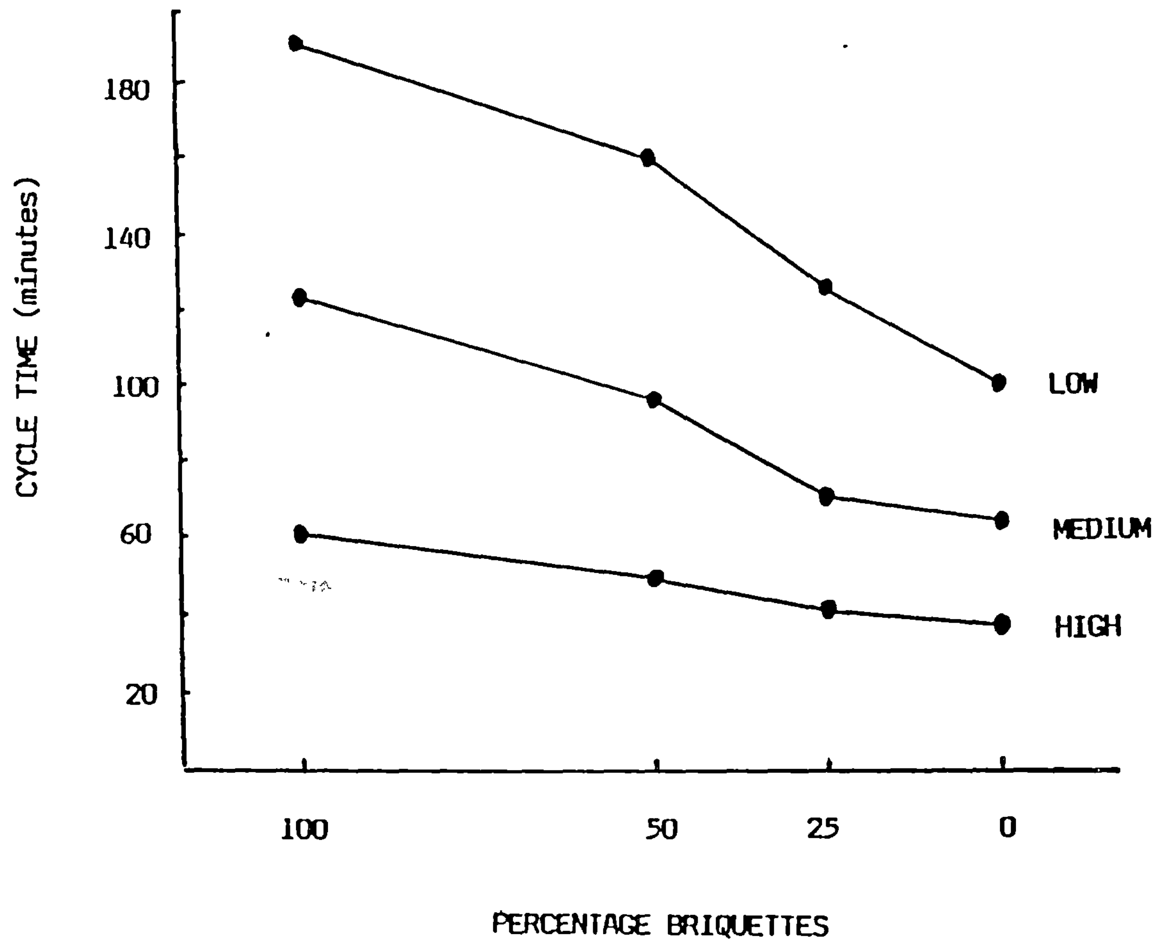


Figure 4.4. Effect of fuel mix on cycle time for the three burn rates in the Arrow 1800A.

results show that briquettes significantly improve this particular heater's performance in this regard.

4.8.2 Stack Vista Heater

(i) The Stack heater showed similar performance trends to those exhibited by the Arrow. But the problems that arose during the testing of the Stack prevented a more detailed investigation. The joins between the cast iron sections of the firebox were not completely air tight. As the firebox expanded and contracted the air leaks changed in an unpredictable manner making repeat tests quite different at times. Attempts to seal leaks were not successful because it would have meant damaging the outer casing which was not readily removable. But the results obtained do give a general picture of the heater's performance.

(ii) The Stack heater has a different design of firebox to the Arrow. The combustion air system of the Stack is a mixture of an updraft and pre-heated s-draft, whereas the Arrow is only an up-draft. The Stack, while being a convection heater, is not fan assisted as is the Arrow.

(iii) As with the Arrow, the Stack's efficiency increased in going from high to low burn conditions although the increases were not as significant. The overall performance of the Stack compared to the Arrow was not good, the heater was much less controllable than the Arrow. For all fuel mixes the power output on the lowest possible setting were comparable to those exhibited by the Arrow on medium setting.

For a particular average power output the Stack's burn rate was higher than the Arrow's. For example, both heaters operating on high burn with 100% briquettes gave similar average power outputs (14.3 kW for the Arrow and 14.07 kW for the Stack), but the corresponding burn rates were significantly different (burn rates rather than cycle times are compared due to different cycle fuel weights). The Arrow gave a 4.19 kg/h burn rate whereas the Stack gave a 4.71 kg/h burn rate. This is a result of the lower efficiency for the Stack. Such observations can also be seen with other fuel mixes where the burn rate for a particular power output is higher for the Stack. The efficiencies of the Stack for 100% briquettes and 100% wood are similar to the corresponding Arrow results when the fan is not operated.

The average flue temperatures of the Stack run on all wood or briquettes compare slightly more closely to the 'no fan' condition of the Arrow (Table 4.5).

Again, these results indicate the need for greater heat exchange efficiency to overcome the high heat loss up the flue at high burn rates.

TABLE 4.5

Average flue temperatures for the Stack and Arrow heaters.

	average flue temperatures (degrees C)	
	wood	briquettes
Stack	597	545
Arrow (no fan)	600	585
Arrow (fan)	573	497

4.8.3 Heatcharm Heater

(i) Of the three mixes used without the grate the 50/50 mix gave the highest average efficiency (55%) and the 100% briquette mix gave the lowest (48%). The variation between the highest and the lowest average result was significant at 7 percentage points, however, there was some overlap of efficiency for different fuel mixes when individual test cycles were considered.
It should be noted that the test results obtained for 100% briquettes were only approximate since the length of the cycles (greater than three hours) meant time resrictions prevented them being monitored to completion. However, the values obtained do give a reasonable indication of the performance of briquette combustion in the appliance.

The test conducted with 100% briquettes with the addition of a grate were remarkably different from those results obtained when no grate was present. Use of a grate increased the average efficiency by 8% to 56%. This result is more like that obtained for the Arrow heater when burning 100% briquettes.

These results and visual observations indicate the grate increased air circulation around the briquettes leading to a greater combustion efficiency which is supported by the other measured parameters.

The use of 50% wood (no grate) gave a similar average overall efficiency (55%) to 100% briquettes with a grate and it seems likely that the presence of the wood facilitated combustion air penetration into the fuel bed. On this assumption one would expect that 100% wood would give the highest overall efficiency result, however this was not the case. The average power output for 100% wood was the highest at 13.1 kW and decreasing to 5.7 kW for 100% briquettes. This would suggest better combustion efficiency for 100% wood and this is supported by the emission results (section 3.3). It seems, then, that the low overall efficiency for 100% wood could be due to excessive heat loss up the flue, hence a lower transfer efficiency.

4.9 Concluding Remarks on Performance

The results of this series of tests show that in heaters with underfire air briquettes are a very satisfactory fuel. They can burn briquettes alone or in various proportions mixed with wood.

However, in a heater with no grate, burning of 100% briquettes does not give a good performance. This is improved if wood is introduced into the fuel load.

Power, or heat output rate, is one of the key performance parameters that a consumer will look for when buying a heater. The maximum power of the two heaters tested was not significantly different when burning either briquettes or wood. This is seen as a positive feature because a heater correctly sized for a particular heating task when fuelled with wood will still be suitably sized if fuelled with briquettes.

The briquettes are a more uniform fuel than wood. Their small, regular shape means that the fuel load does not 'collapse' causing changes in power output as may happen with wood. Their higher fixed carbon content means that they burn with a longer char burning phase than wood. This leads to longer burning cycles, but the longer cycles mean a greater swing in power over the cycle than observed with wood. This swing, which on a high burn rate is typically 4 kW (from 12 to 16 kW), will be partly smoothed out by the thermal mass of the room being heated. On lower burn rates the swing is proportionally less.

The overall efficiency of the Arrow heater is slightly higher when briquettes are burnt. The improvement of about 5 percentage points is significant and appears to occur at all burn rates. With the Heatcharm (no grate) the overall efficiency was greatest when a 50/50 fuel mix was used, indicating the need for air penetration into the burning fuel.

Perhaps the biggest advantage of briquette or briquette/wood fuels is the longer burn time for a given weight or volume of fuel. This means less frequent refuelling and can make the difference between easily burning overnight and failing to do so.

PART TWO

5. THE DESIGN, DEVELOPMENT AND TESTING OF A BRIQUETTE BURNING HEATER

5.1 Introduction

This part of the research was aimed at the design and development of a briquette burning heater prototype with the final product being considered for commercial sale.

In designing a heater for residential use, there are two objectives that need to be addressed. Each objective, consisting of several interrelating factors, is listed and discussed below:

1. Technical objectives:
   i. burn briquettes,
   ii. good efficiency,
   iii. adequate power range, and
   iv. low emissions.

2. Marketing objectives:
   i. appropriate size of heater,
   ii. ease of operation,
   iii. adequate burn time, and
   iv. flame visibility.

The ability of the heater to burn briquettes was paramount since this was the main aim of this section of the research.

The efficiency factor is very important in today's environmental and economic climate. Heaters must be capable of delivering the maximum amount of useful energy from the fuel used. Some of the better solid-fuelled heaters on the market today are capable of delivering an overall efficiency of 60%. In light of this, an efficiency of 60% or greater was aimed for.

The main purpose of using a heater is to provide heat to the user, and so the rate of heat output, or power, must be controllable and suited to typical domestic needs. Hence, the heater must be able to operate efficiently over a wide range of heat outputs. To provide a range of comfortable heat outputs, a range of about 5 to 12kW was decided upon as a design objective. This range is what most conventional heaters fall in.

The factor of heater emission rate is primarily a health consideration and, in some countries, is governed by strict legislation. This factor is also closely linked to the efficiency of the appliance. Hence, the heater should operate with a low emission rate. The United States Environmental Protection Agency had set a maximum level of 7.5 g/h for non-catalytic heaters manufactured after 1/7/90. This is considered quite a tight limit, but one which the better woodheaters are achieving and so it was selected as the design goal.

The size of the heater should be similar to conventional residential heaters. This factor is important when considering the cost and appearance of the appliance. The heater must also be easy to operate, since consumers will not want to be continually adjusting the controls. Hence the heater should be designed with a minimum of easily usable controls.

The time between fuel loadings should be as long as possible. The ability of the heater to burn overnight is also an important aspect. Most of the popular models of heater on the market today are capable of burning for at least 8 hours before refuelling is required, so a target burn time of 8 hours or greater was decided upon for this heater.

Not only does a heater function as a heat source, it is also often a focal point in the room, so the user should be able to see the flames of the burning fuel. Hence, a glass door would be required.

Some of the above points can put difficult boundaries on what the heater should achieve since some factors require a compromise on other points. For example, if size and cost were not a restriction, then designing a heater that was very efficient, with a low particulate emission rate, would not be too difficult.

The design and development of residential heaters is mainly one of trial and error. This does not mean that one starts from scratch, but rather all the available data gathered from tests, experience and basic principles is put to use. Even so, the final product may not perform to the standard predicted by such theoretical and practical input.

The tests conducted and reported in Part 1 of this thesis give a good idea of the heater design required to give a good overall performance in terms of efficiency and low emissions when briquettes are used. Hence the heater designed is a result of all the data gathered from tests conducted on the various heaters with briquettes, wood and briquette/wood mixes reported in Part 1 of this thesis, as well as conclusions drawn from research reported in the scientific and technical literature. In addition to this, valuable information was gained from discussions with experienced people involved in the heater industry, as well as the experience accumulated from 10 years of research by staff at the University's Home Heating laboratory.

5.2 Heater Design

5.2.1 Grate

The first aspect conidered, was the question of whether the heater required a grate. The test results indicate this to be so. Due to the geometry and size of the briquettes a grate is required to ensure adequate combustion air reaches all the fuel, since the fuel has a tendency to stack in such a way as to prevent this. This is reflected in both the efficiency and emission results on the Heatcharm heater from tests done with and without a grate.

TABLE 5.1

Summary of data from emission tests on the Heatcharm heater with and without a grate when fuelled with briquettes on the maximum heat setting.

FUEL	No. TESTS	GRATE	AVERAGE EMISSION g/h	AVERAGE EFFICIENCY %
100B	3	YES	4.99	58
100B	2	NO	32.22	45

100B = 100% Briquettes

The emission and efficiency results when a grate is present are far superior to those without a grate. Such conclusions are also supported in the literature. 'The efficiency of a grateless stove is always inferior to that of one with a good grate' (Winkelmann 1955). The design of the grate itself also plays an important role on the heater's performance. The design of a grate is largely dictated by the fuel to be used. Since there has been very little research reported on the use of brown coal briquettes in residential heaters, the grate used in this research was developed by trial and error.

5.2.2 Combustion System

The next step considered was how the combustion air should flow through the firebox. The choice made, was one where air would enter the firebox and be drawn through the burning fuel bed. This system was chosen instead of an 'S'- Draft or overfire pathway due to greater air penetration into the fuel bed.

The decision of using a grate and a combustion air pathway that draws the air through the grate and fuel, raises the question of which direction the air should take, that is, updraft or downdraft. The decision made was to go downdraft because the literature suggests this would give more complete combustion. This would result in higher overall efficiency and lower emissions. Research conducted by Barnett (1982) on 14 heater types using wood as the fuel revealed the downdraft design to be at the lower end of emission rates. A discussion on downdraft systems by Winkelmann (1955) states that a downdraft system guarantees good combustion because the gases pass first through the grate which is very hot.

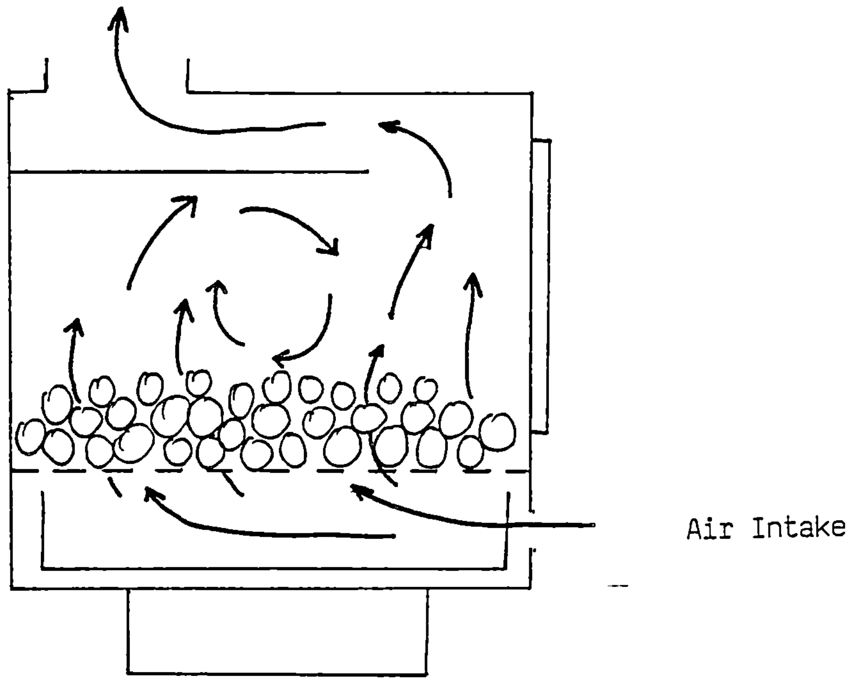
Such conclusions about downdraft are also indicated by the work done on emissions with the heater designs tested and reported in the first part of this thesis. This is discussed below.

Particulate emissions are a result of volatiles escaping the combustion zone without being burnt. In order to prevent, or at least reduce, this the volatiles must be kept in the immediate vicinity of the hot combustion zone together with an adequate quantity of air to ensure combustion.

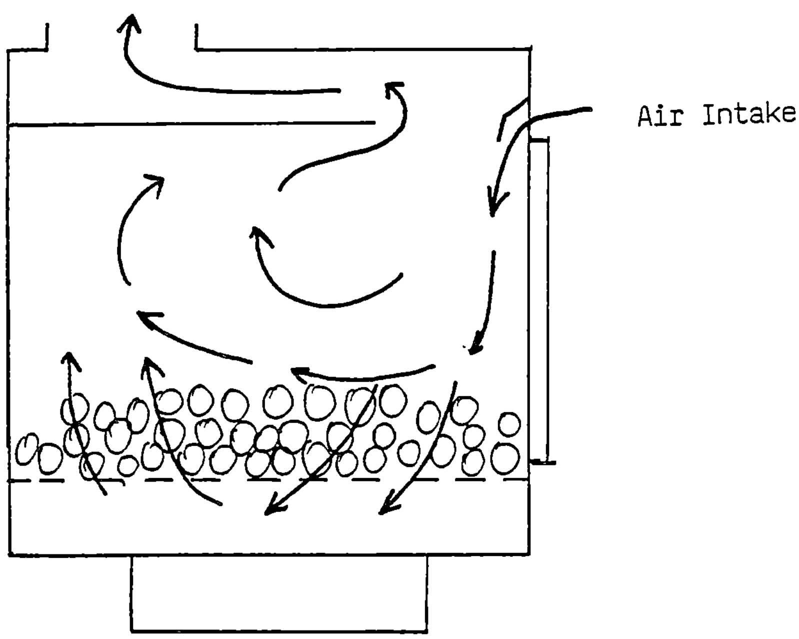
Considering an updraft design; combustion air enters the firebox from under the grate and is drawn up through it, through the burning fuel bed and then into the flue. Such a pathway can result in some of the volatiles released by the top outer layer of the fuel pile being carried away from the combustion zone without being ignited. The quantity of volatiles escaping in this manner would be greater during low burn rates due to restricted air flow and cooler firebox conditions. The result being high particulate emissions.

If, however, the direction of combustion air is reversed, as is the case with a downdraft design, then the volatiles released from the outer layer of fuel would be drawn directly into the combustion zone where temperatures are high and so increasing their chance of ignition. Although no downdraft heater was tested, the emission results of the Arrow and Heatcharm (with grate) gives some indication of this combustion air pathway concept. This is illustrated in Figure 5.1. The schematic diagrams show the probable combustion air pathway in both heater designs.

The Arrow is a true updraft heater and one would expect the air pathway to look something like that shown in Figure 5.1. There would be little air recirculation back into the fuel bed since this would be prevented by the incoming air flow. The Heatcharm with the grate



Arrow



Heatcharm (with grate)

Figure 5.1. Schematic diagram of the air flow in the Arrow and Heatcharm with grate modification.

modification is not a downdraft design, however it would be expected to exhibit some downdraft flow. As indicated in the diagram some of the combustion air would pass through the fuel bed and grate and into the ash collection area. In fact, this design shows downdraft, updraft and 'S' draft characteristics. The circulation of air would carry volatiles down through the burning fuel bed as would a true downdraft heater. The modified Heatcharm emission level was found to be 4.99 g/h when burning briquettes while the Arrow resulted in 36 g/h under the same conditions (see Tables 3.5 and 3.6, Section 3.3.2).

These results seem to support the idea that a downdraft pathway may give lower emissions. Further support is given by the emission results of the Heatcharm with no grate (32 g/h). Without a grate, the Heatcharm is purely an 'S' draft design and the high emission rate (without a grate) would seem to rule out the modified Heatcharm's low emission rate being attributed to the 'S' draft character present.

One other factor which necessitates the production of low emissions is the odour of burning briquettes. Such odours are directly attributed to the escape of combustible gases and so are greatly reduced when low emisssions are achieved.

5.2.3. Heat Transfer

The main purpose of using a heater is, of course, to heat a desired space such as a lounge-room. In order for this to occur, the heat released by the combusting fuel has to be transfered from the heater into the surrounding space. To obtain the maximum amount of heat transfer, whether by radiation and/or convection, there must be adequate heater surface area through which this can occur, otherwise much of the heat will escape up the flue and be wasted. However, if too much heat is removed from the gases in the firebox then there is the chance that combustion efficiency will suffer due to excessive cooling of firebox conditions. The tests conducted on the Arrow heater regarding the flue gas temperature when wood or briquettes are used with or without the convection fan operating, indicates the sensitivity of briquettes to firebox temperature (see Table 4.4, Section 4.8.1). In light of this possibility, the most logical point to affect heat removal is after the gases have left the combustion zone but before exiting to the flue.

Although some heat will be transfered through the flue surface, the amount will be governed by its design and position. If the flue is insulated, then the rate of heat release would be small compared to an uninsulated one. If the flue is not exposed to the room air, by being placed in an existing fireplace, then very little useful heat would be extracted. Hence, most of the heat needs to be retrieved before the hot gases enter the flue, not forgetting that if too much heat is removed then the problem of creosote deposition may arise, as well as retarding the natural draft that affects combustion air intake.

So the objective was to extract as much heat as practicably possible from between the exit of the combustion zone and entry to the flue. To achieve this, the gas pathway should be as long as the heater design and size will allow and the hot gases exposed to a large surface area through which heat transfer can take place.

5.2.4 Fuel Loading

The method of fuel introducton into the firebox can play a an important part in the performance of the heater, especially where particulate emissions are concerned. There are basically two methods of fuel introduction;

1. Batch feeding, and
2. Continuous feed.

The batch feeding method is the most common in today's heaters. This involves loading the firebox with a quantity of fuel every time the fire needs replenishing. Such a method can have adverse effects on particulate emissions. The introduction of a large quantity of cool fuel to the firebox greatly reduces the fire's temperature. This is because a large amount of heat is required to raise the temperature of the new fuel to affect its combustion. While this is happening, large quantities of gases can be released and escape unburnt, resulting in high emissions.

With a continuous feed process, only small quantities of fuel are fed, usually automatically, into the combustion zone at a rate dictated by the burn rate. Depending upon the design of the system, the fuel can be preheated before its introduction. Such a method eliminates the problems outlined above with the batch feeding method. The introduction of fuel, usually via a storage hopper, ensures steady-state combustion conditions can exist (Dobson 1986) and so a reduction in emissions is achieved.

One other advantage of using a hopper type system, is that fuel handling is kept to a minimum. While using briquettes for the study reported in Part 1 of this thesis, two main characteristics were noted: i) briquettes are extremely dirty and, ii) due to their size and shape, are difficult to handle. Dealing with these characteristics would not be met with enthusiasm by consumers.

In order to overcome these two perceived problems it was thought necessary that the heater should be able to burn for as long as possible before the need to refuel, and when refuelled, done so with minimum fuel handling. This could be achieved by using a fuel storage hopper that continuously fed the fire.

Hence, from the above analysis it was decided that the heater should be designed with a hopper incorporated into the appliance and operated by gravity feed.

Being an inbuilt hopper and inside the heater, would require the stored fuel to be well protected from the heat of the burning fuel to prevent it from igniting. Also, the lid of the hopper, through which briquettes would be poured, would need to be air tight to prevent the fire burning up into the hopper.

5.2.5 Viewing Door

In order for the user to see the combustion flame, a viewing door with a glass panel must be present. This viewing door would also be used when lighting the fire and cleaning the firebox. To prevent the glass from getting dirty, the combustion air intake would be positioned in such a way as to direct the incoming air down over the inside of the glass panelled viewing door. This 'door air-wash' technique is widely used by manufacturers and helps prevent soot build-up on the inside of the glass.

5.2.6 Design Summary

In conclusion, the main points decided upon regarding the design of the heater are summarized below;

1. The combustion chamber would be a downdraft design to obtain a better, more efficient, clean burning heater.

2. Fuel loading would be done through the top of the heater via an inbuilt gravity feed storage hopper.

3. The heater should have high heat transfer capability in the region where the combustion gases leave the combustion zone and before entering the flue.

4. The combustion air intake would be at the top of the firebox and in such a way as to direct the air over the inside of the viewing door glass.

5. The heater would have a grate.

Using these guidelines a briquette burning heater prototype was designed, built and tested.

5.3 DESIGN AND TESTING; MODEL 1

5.3.1 Design

The initial design, named MK1, resulting from the design criteria discussed above, is shown in Figure 5.2. The first step in designing the heater was to prepare a set of drawings which incorporated as many of the design features as possible. From these, a cardboard model of the firebox was made and the drawing revised. Once the drawings were considered complete, they were given to a local steel fabrication factory and a prototype constructed.

The complete set of construction drawings are shown in Appendix A.

As mentioned previously, heater design is one of trial and error and thoery does not always translate into practice. Unfortunately, the operating performance of this heater revealed many serious problems. These being listed below.

1. Initially, the intention was to start the fire in the ash tray to induce draft. However, this was found to be an unsatisfactory technique due to excessive smoke release into the room. Once the flue heated enough to induce natural draft, the smoke leakage ceased. However, when the viewing door was opened or the ash tray removed, large quantities of smoke escaped into the room indicating that the downdraft flow was interrupted.

2. When a fire had been well established and the burn rate was at a maximum, it was observed that the inner skin of the hopper was subject to extreme heat and in some places glowed red. This would result in greatly shortening the steel life.

3. The fuel had difficulty in falling from the hopper exit

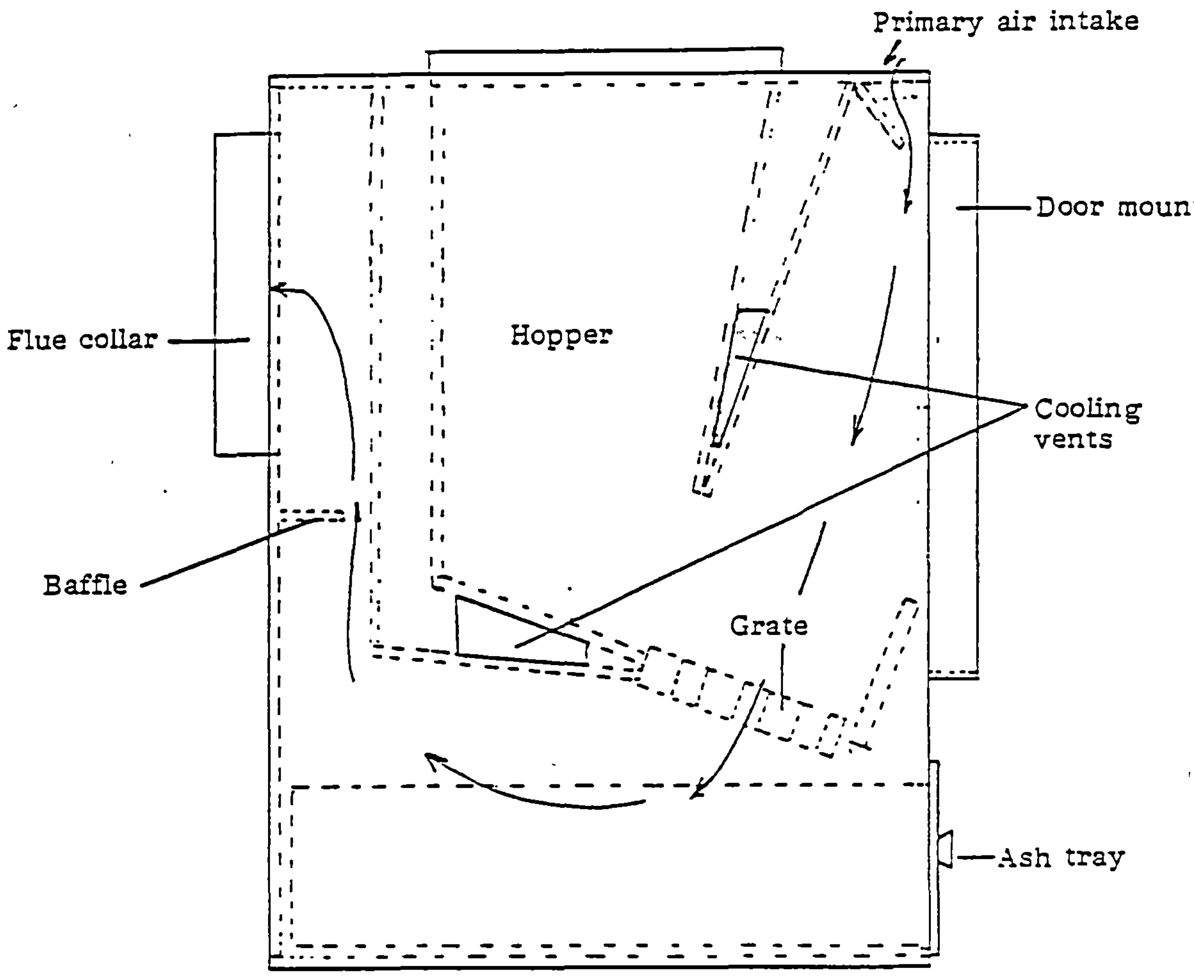


Figure 5.2. Side view of the first heater design, MKI. Arrows indicate direction of air flow.

onto the combustion zone. This was found to be caused by a too narrow hopper exit, non-parallel hopper walls and the grate (and combustion zone) being situated too far forward from the hopper exit. All this resulted in briquettes becoming jammed inside the hopper and the fire running out of fuel. This regular occurrence made performance testing difficult and reduced the accuracy of the results. However, the results obtained did enable a reasonable assesment to be made.

4. After the heater had been operated a few times it was noticed that the grate had started to bend. This was attributed to a lack of support for the grate, and so with continued heating and the constant weight of fuel the grate gradually bent downwards.

5. The ashtray was found to be lacking in size. During heater operation it would not take long before the ash level in the tray was touching the underside of the grate. This resulted in blocking the air flow and so the ash tray required frequent emptying.

6. The size of the hopper was found to be inadequate since it needed refilling frequently, a requirement the hopper was intended to reduce.

5.3.2. Performance

The few tests that were conducted on this model indicated a lack of overall efficiency, this being in the range of 45-50%. This low result was thought to be mainly due to the heater's low heat transfer efficiency which was indicated by the very high flue gas temperatures and corresponding low heat outputs.
Due to the very poor performance results, no emission rates were obtained. However, visual inspection indicated the emission rate of the heater to be quite low compared to the other designs tested. Also, the distinctive odour present when other heater designs were tested, was only just detectable with the MK1.

5.3.3 Conclusions to the MKI design.

Due to the number of problems associated with this design, modifications to the heater itself were not attempted. Keeping in mind the problems, it was decided that a new heater be designed which would eliminate the above problems while still maintaining the overall design concept. In this respect the MKI model played an invaluable role in this research. This also shows the trial and error approach to designing heaters.

5.4 DESIGN AND TESTING; MODEL 2

5.4.1 Design

In designing a second heater model, all the problems associated with the MKI design were taken into account in order to prevent repeating them. The changes that were made are listed and discussed below.

1. Improved Heat Transfer: To obtain a better heat transfer efficiency a greater retention time of combustion gases within the heater was needed. To achieve this, the path these hot gases was made to travel was greatly increased. The new design also increased the surface area through which heat transfer could be affected.

2. Bypass: The problem of initiating a downdraft air flow and smoke release when the ash tray was removed or the viewing door opened on the MKI was overcome by introducing a bypass system. A bypass system enables gases to exit the firebox and bypass most of the heat exchange area.
   Bypass holes, which could be closed off easily, were placed in the top left and right sides inside the firebox combustion chamber. These holes, when open, would allow the heater to be operated in an updraft mode where air would be drawn in through a controlled opening in the ash tray door, up through the grate and fuel and into the flue via the bypass. After lighting the fuel, and the flue gases being hot enough to affect a strong draft, the bypass and ash tray opening could be closed, thus inducing a downdraft mode by drawing air through the intake at the top of the heater and down through the fuel and grate.

3. Hopper Isolation: The problem of the hopper overheating was addressed by increasing its isolation from the combustion zone and ensuring adequate ventilation. The increased ventilation should also contribute to heat

transfer and so improve the overall efficiency.

4. Fuel Feeding: By eliminating the slope of the hopper walls in the MKI design, the jamming of briquettes inside the hopper would be prevented. The hopper exit was also moved closer to the combustion zone to ensure the fuel would continue to replenish the fire.

5. Grate Support: Grate bending due to the weight and heat of the burning fuel was prevented by introducing supports on all sides of the grate.

6. Ash Build-Up: A larger ash tray was needed, so a pedestal which would house the ash tray was incorporated into the design. Having a larger ash tray would reduce the number of times it would require emptying compared to the MKI at a given burn rate.

This second design, named MKII, resulting from the above alterations to the MKI design is shown in Figures 5.3, 5.4, 5.5, 5.6, 5.7 and 5.8. These diagrams show various cut away and section drawings of the heater and indicate the pathways taken by the combustion gases and hopper ventilation air flow. The first step in designing this heater was to prepare a set of drawings which incorporated the above alterations. From these drawings, a cardboard model was made and the drawings revised where necessary. Once the drawings were considered complete, they were given to a local steel fabrication factory and a prototype constructed. Detailed construction plans for this heater can be found in Appendix B.

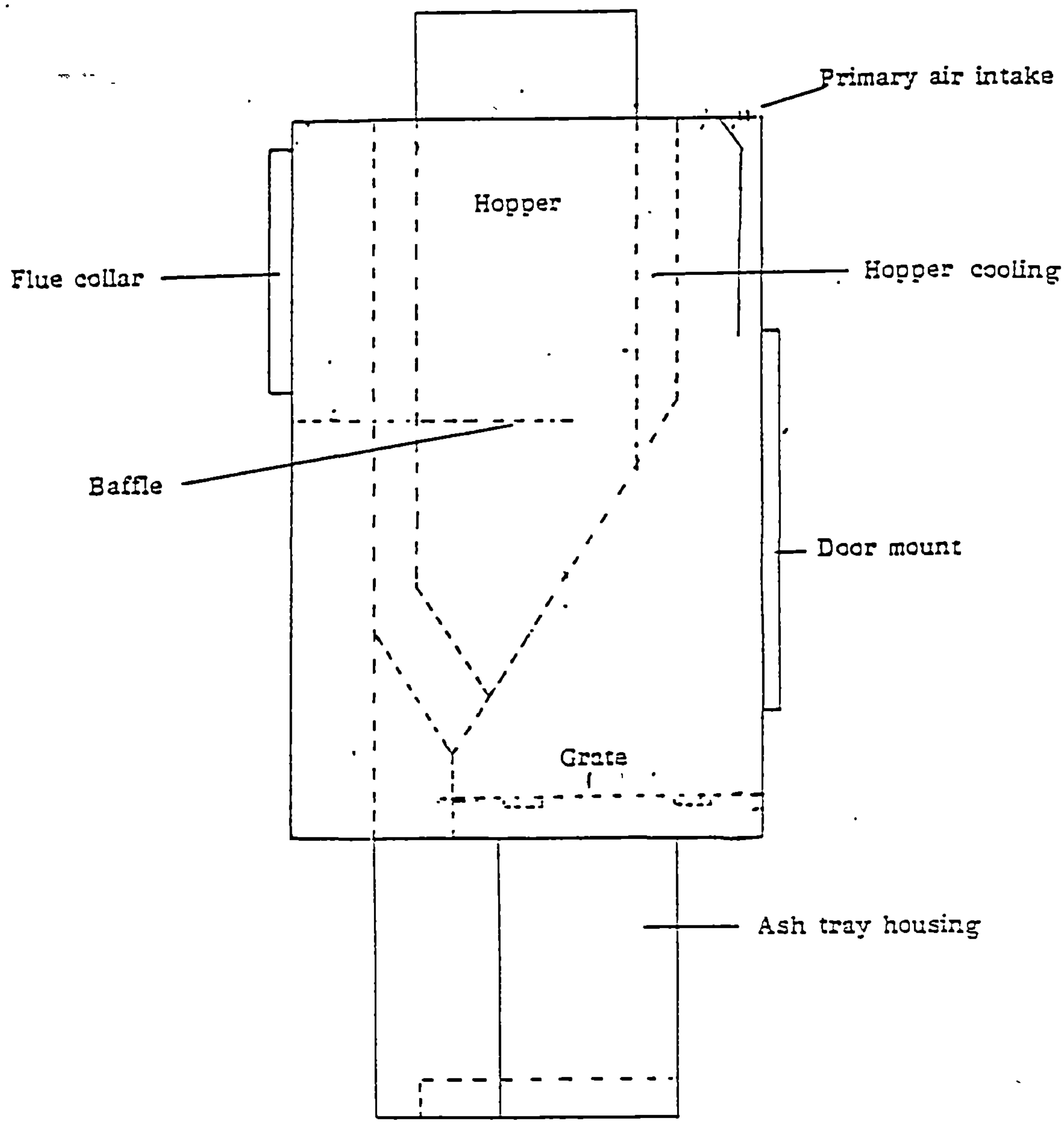


Figure 5.3. Side view of the MKII showing basic design features.

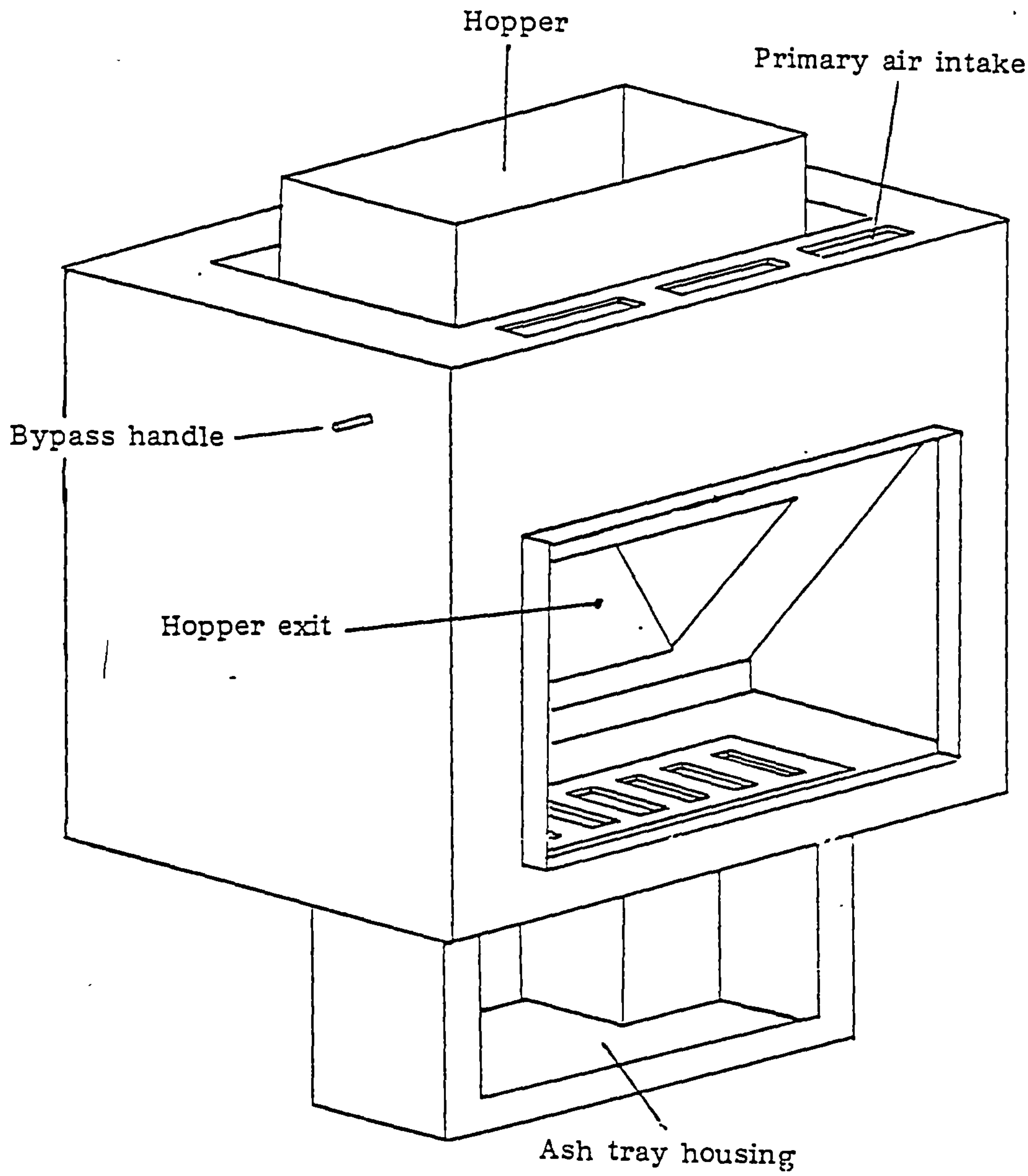


Figure 5.4. Isometric view of MKII without viewing door, ash tray, or hopper lid.

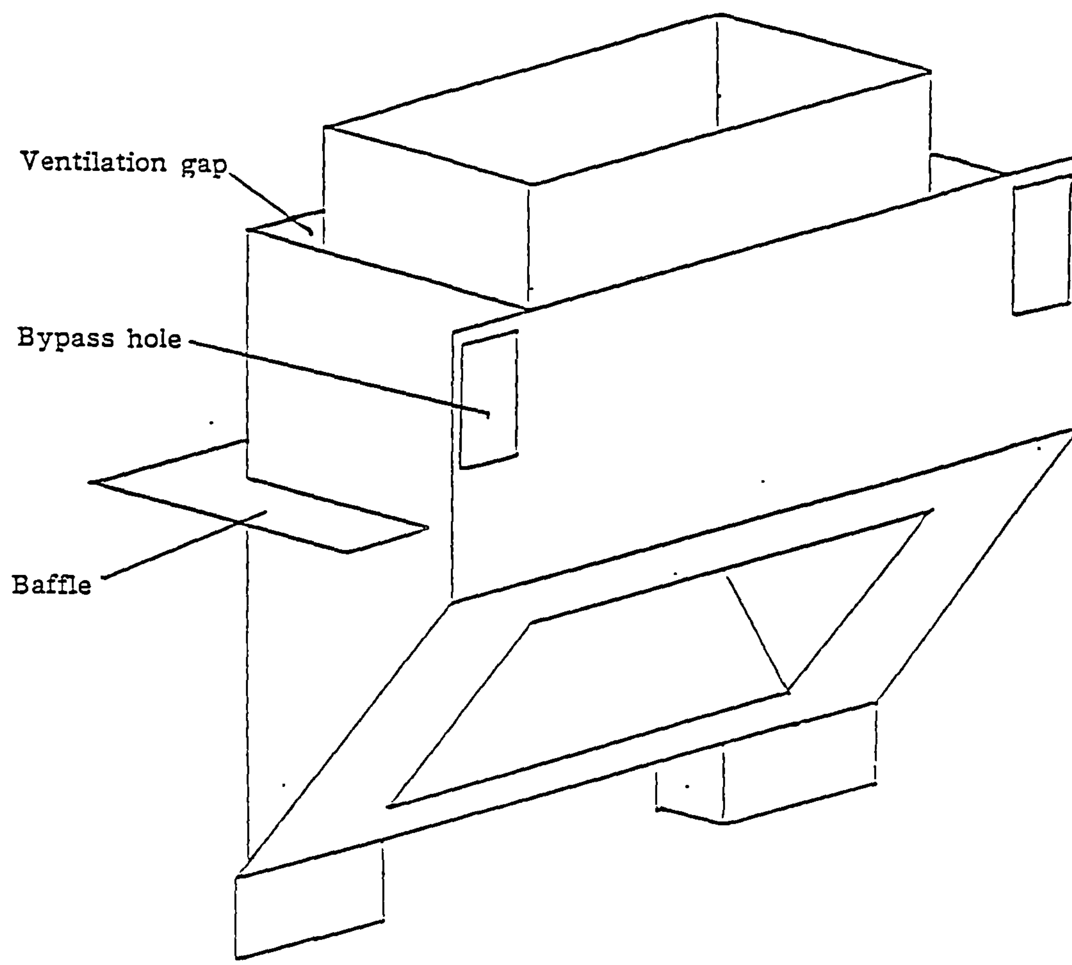


Figure 5.5. Isometric view of hopper.

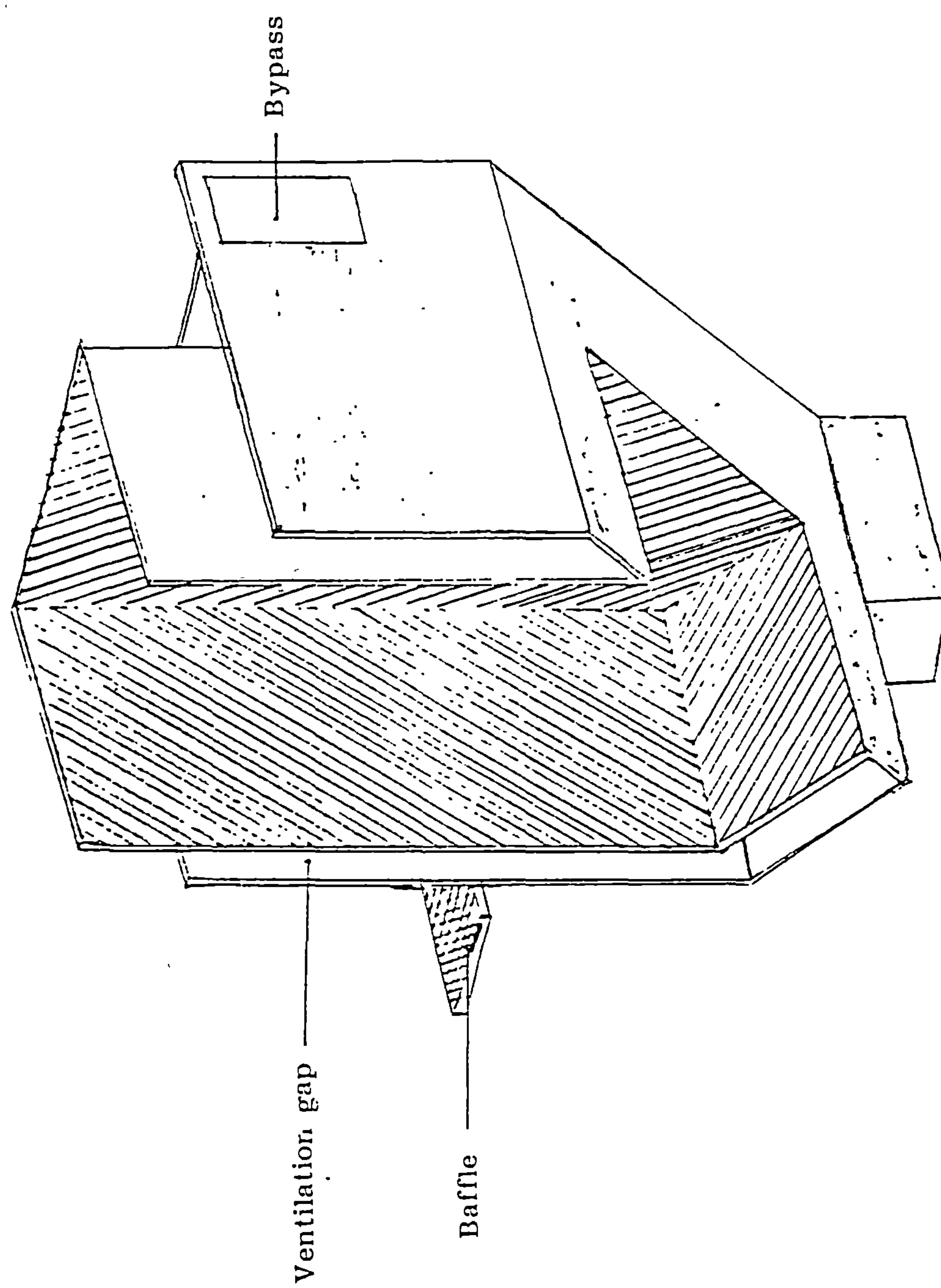


Figure 5.6. Cut-away section of hopper showing extent of ventilation gap.

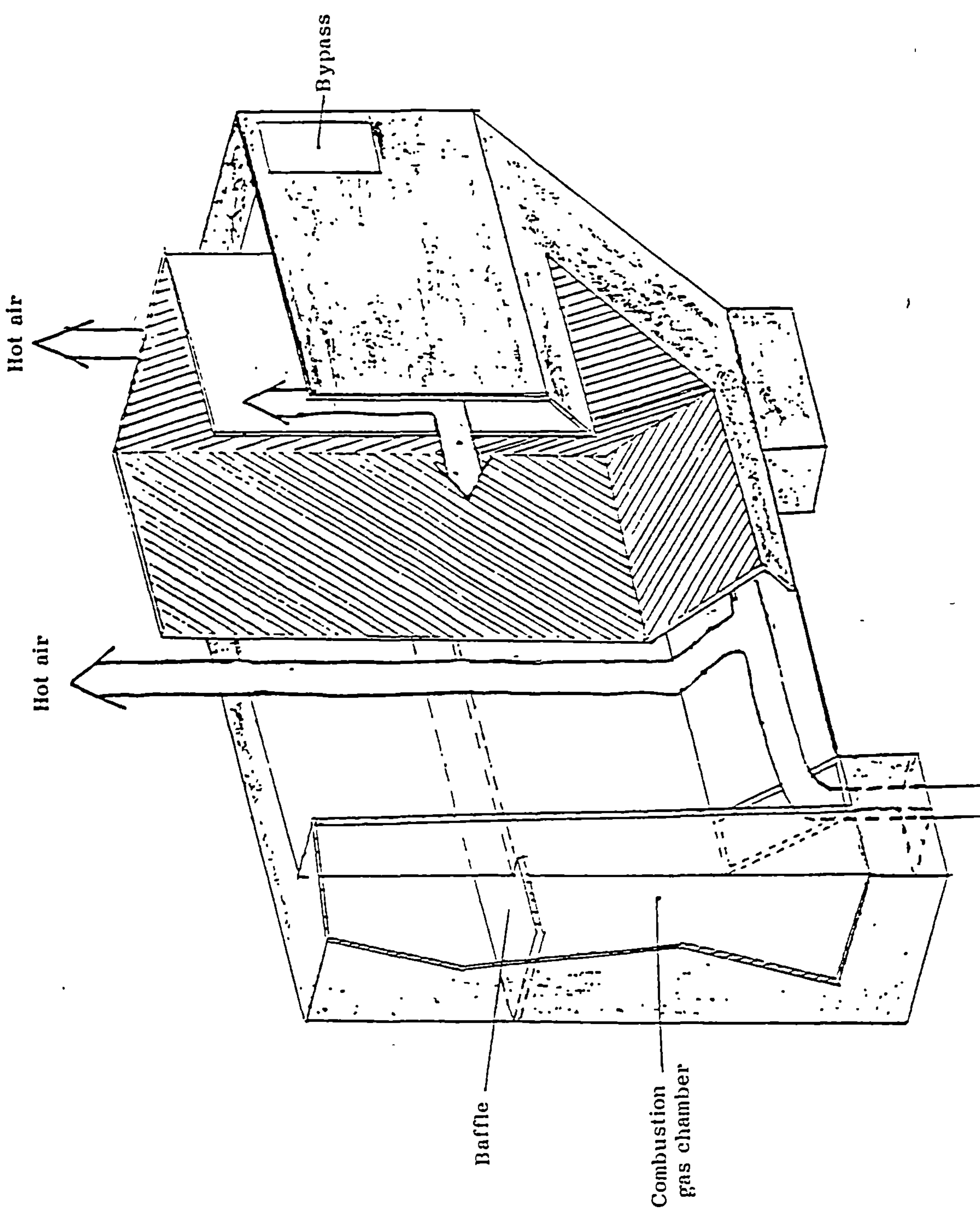


Figure 5.7. Pathway of hopper ventilation air. Front end of firebox not shown.

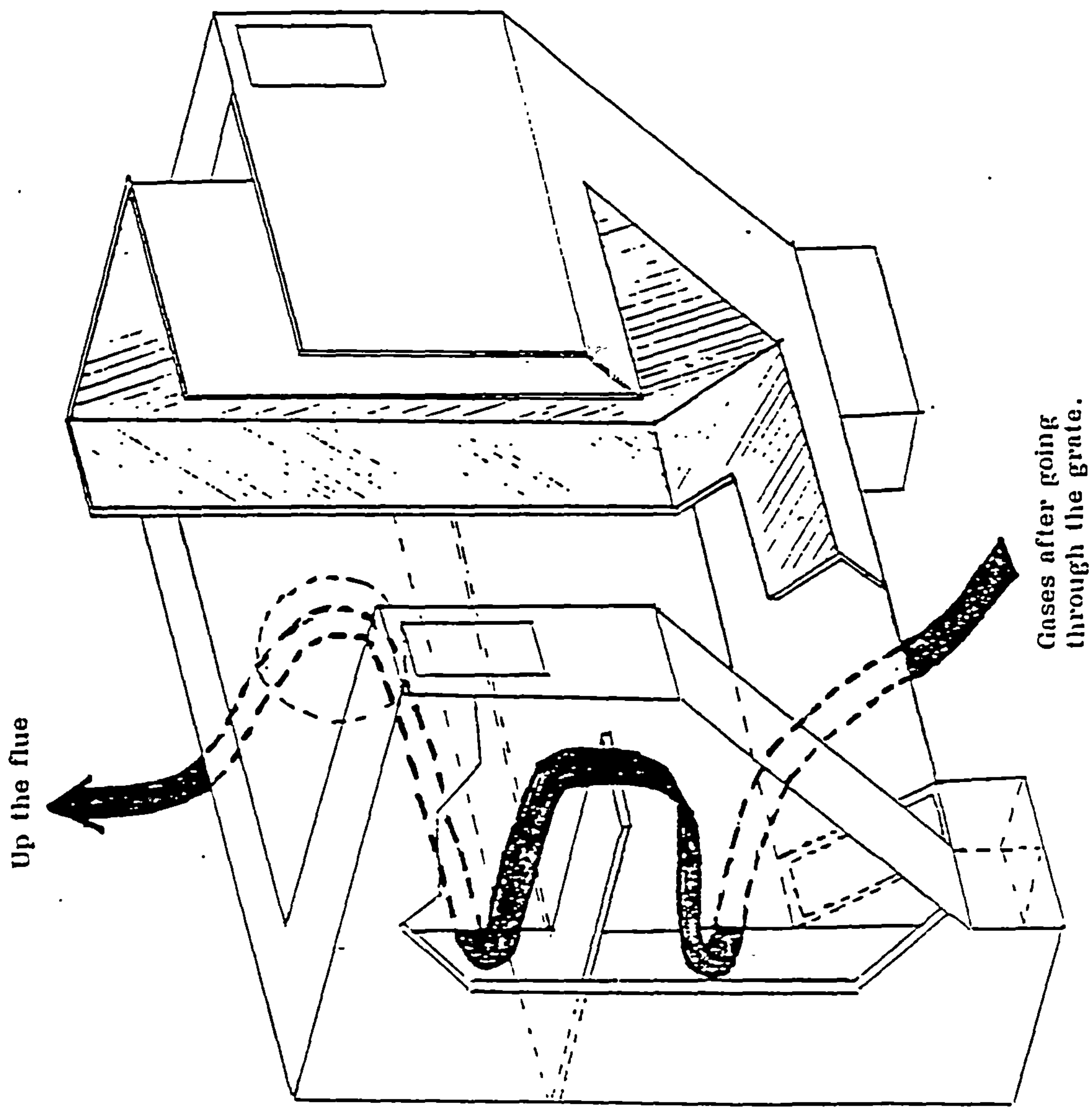


Figure 5.8. Diagram of combustion gas pathway.

5.5 OPERATING AND TEST PROCEDURES

5.5.1 Initial Operating Problems

The first problem to be encountered was the hopper exit. This proved to be a little too large since some briquettes spilled up against the viewing glass door when the hopper was loaded. This was easily remedied by welding a 4cm wide steel strip across the top of the hopper exit

During some of the initial testing the grate became blocked by small fragments of fuel. This resulted in restricted air flow and a dramatic drop in power output. Several grate designs were made and tested to overcome this problem. Figure 5.9 shows the various designs. The most successful design proved to be the one with 7 slots (grate 4).

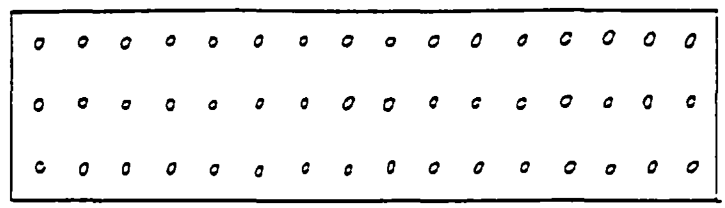
5.5.2 Ignition

To light the heater, enough briquettes were placed in the heater via the hopper to cover the grate, but not so much as to start filling the hopper. The main viewing door was then opened and several large fire lighters were placed amongst the briquettes and ignited. The bypass was opened and the ash tray pulled out slightly to allow air to enter the ash tray housing and be drawn up through the grate and fuel, then through the bypass holes and out up the flue. The viewing door was of course closed once the fire was lit. When the fire was well established the bypass and ash tray were closed. At this point the flue gas temperature was high enough to initiate the downdraft combustion air flow. The hopper was then filled as required.

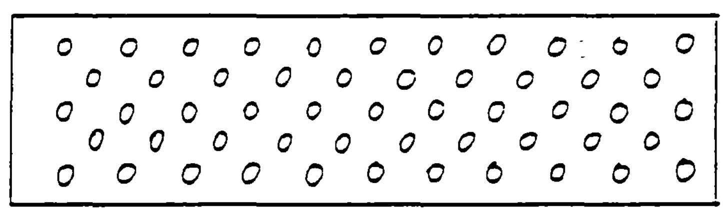
The burn rate was controlled by adjusting the amount of air entering the primary air intake.

5.5.3 Test Procedures

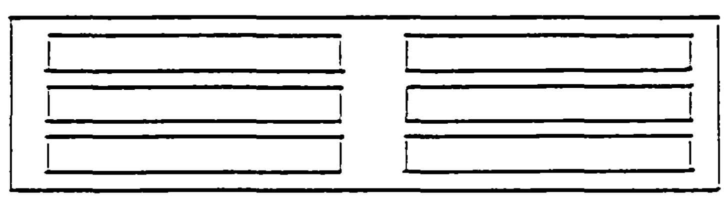
The test procedures used were basically those set out in 'Draft Test Method for Performance Rating of Woodheaters' (Todd and



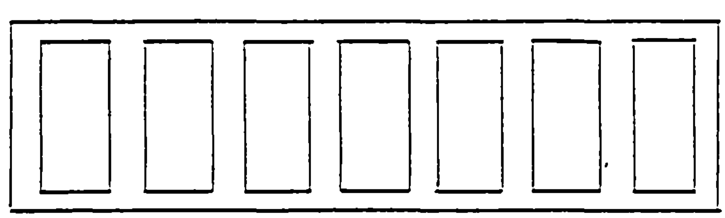
Grate 1: 10 mm holes



Grate 2: 18 mm holes



Grate 3 (140 x 13 mm slots)



Grate 4 (100 x 30 mm slots)

Figure 5.9. Type of grate design used.
Grate 4 was the most successful.

Sawyer,1987).
Testing the efficiency and emission rate was done in the University's Home Heating Laboratory calorimetry room and involved the following procedure:

1. The heater was lit as described above (5.5.2).

2. Once the heater was in the downdraft mode the hopper was filled and the primary air intake adjusted to give the required burn rate.

3. After operating temperatures had been reached the fuel load was allowed to burn down to a weight of 2 to 3 kilograms. At this weight the remaining fuel mainly is burning charcoal and the grate was well covered.

4. The electronic scale upon which the heater rested was tared to give a zero weight reading.

5. The hopper was the filled with a test load, the weight being 3 to 6 kilograms depending on the burn rate being tested, and the testing commenced.

6. The test cycle ended when the scale reading returned to the zero reading.

5.5.4 Fan Forced Convection

To better simulate a convection heater, that is a heater with a decorative outer cover, a makeshift convection cover was made from tin sheet which, when placed around the heater, enclosed the rear and both sides of the heater. This was used in all tests. This cover was placed around the heater so that a gap of 4 to 5 centimeters remained between it and the heater. The cover rested on the floor and had a height of 50 centimeters (20 centimeters short of the top of the firebox). In front of the heater and at floor level, a propeller type fan was placed which when operated, directed an air flow at the bottom of the heater. This fan forced air flowed around

the heater, being guided by the tin sheet cover.
Some of the tests were conducted with the fan on and others with the fan off. Tables reporting the test results indicate the situation applied.

5.6 MODIFICATIONS AND TESTING

Initial testing done on the heater indicated that the basic design was satisfactory. However, a series of minor modifications were made to 'tune' the design. The heater was then retested to establish what effect the changes had on performance. These modifications are listed and discussed in the following sections.

5.6.1 Secondary Air

A. Top of hopper exit: Secondary combustion air was introduced by positioning a stainless steel 12.5mm pipe, with holes drilled along its length, at the top of the hopper exit. Both open ends of the pipe extended out of the firebox. See Figure 5.10.
B. Directly below the grate: Secondary combustion air was introduced under the grate by drilling a hole through the left side of the firebox wall, just below the grate. A 25mm pipe with air holes and one end blocked was positioned under the grate with the open end exiting through the drilled hole. The air holes were directed downwards to prevent ash blockage. See Figure 5.10.

These pipes would become very hot during the operation of the heater and so some preheating of the secondary air would occur.

After a set of tests was done with this setup, a further modification was done. The secondary combustion air was preheated by a channelling system which covered the secondary air intakes as shown in Figure 5.10. Air enters these channels at the rear of the heater.

By introducing secondary air into the heater it was anticipated that combustion efficiency would be increased and hence the emission rate would be reduced.

5.6.2 Firebricks

Firebricks were placed on the base and walls of the ashtray housing (pedestal). These were about one centimeter thick. This would maintain the highest possible temperatures in this area where volatiles were burning. The main effect of this was to reduce emissions.

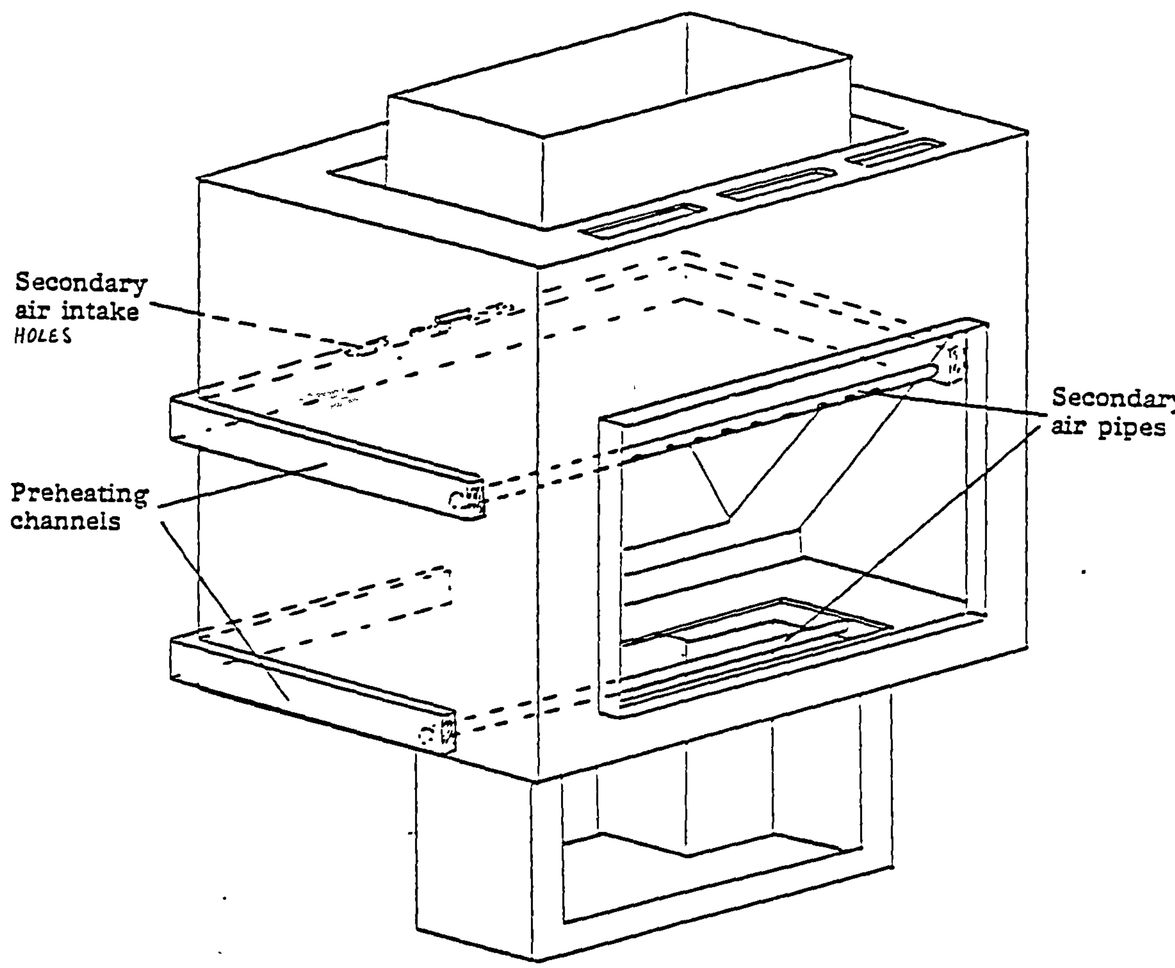


Figure 5.10. Diagramm showing secondary air design.
No grate is present.

5.7 PERFORMANCE RESULTS

Tables 5.2 to 5.5 below give a complete list of results obtained from testing the heater with and without modifications. The data is grouped into sets according to what modifications were done. A full description of the test procedures is given in Appendix C.

TABLE 5.2

Performance results from tests conducted with no secondary air or firebricks.

Test	Ave. Power kW	Efficiency %	Emission Rate g/h	Burn Rate kg/h wet	Burn Rate kg/h dry	Fan
2	16.57	64.6	6.99	4.10	3.49	on
3	15.00	59.4	4.28	4.04	3.43	on
1	12.04	62.4	8.59	3.06	2.60	on
4	8.10	68.7	4.29	1.88	1.60	on

TABLE 5.3

Performance results with secondary air above hopper exit; no firebricks.

Test	Ave. Power kW	Efficiency %	Emission Rate g/h	Burn Rate kg/h wet	Burn Rate kg/h dry	Fan
5	16.28	65.4	-	3.98	3.38	on
6	15.50	64.4	5.28	3.85	3.27	on
7	6.38	65.9	-	1.55	1.32	on

TABLE 5.4

Performance results with secondary air above hopper exit and below grate; firebricks present.

Test	Ave. Power kW	Efficiency %	Emission Rate g/h	Burn Rate kg/h wet	Burn Rate kg/h dry	Fan
8	8.76	67.2	3.02	2.08	1.77	on
9	7.40	64.2	2.66	1.84	1.56	off
10	4.91	67.9	10.45	1.16	0.99	off

TABLE 5.5

Performance results with preheated secondary air; firebricks present.

Test	Ave. Power kW	Efficiency %	Emission Rate g/h	Burn Rate kg/h wet	Burn Rate kg/h dry	Fan
14	13.33	62.3	2.38	3.35	2.91	on
13	7.75	71.2	2.97	1.70	1.48	off
12	4.92	75.0	3.77	1.02	0.89	off
11	3.41	68.6	5.34	0.77	0.67	off

5.8 DISCUSSION

As the heater was gradually modified with features such as secondary air and firebricks the performance results indicated continuing improvements. The best result were obtained when all the modifications were included. This is shown in Table 5.5.

An average efficiency calculation of the results in Table 5.5 gives an overall efficiency of 69.3%. The power output of the heater is also quite acceptable with a range 3.4kW to around 16kW.

Flame visibility on all burn rates was good and indicated the presence of gas turbulance above the fuel bed. Close inspection through small viewing holes in the wall under the grate, showed flames travelling through the grate and into the ash tray compartment.

The overnight burn capability of the heater is also very good. With a full hopper load, tests show the heater will burn in excess of 15 hours on a low setting.

Also, using the results in Table 5.5 a weighted emission rate can be calculated according to the formula set out by the Environmental Protection Agency of the United States (E.P.A.). The method used by the E.P.A. is one where the emission rates from four categories, dictated by burn rate, are statistically evaluated using the following equation and method.

$$E_w = \frac{\sum_{i=1}^{n} (K_i E_i)}{\sum_{i=1}^{n} K_i}$$

where:
E_w = Weighted average emission rate, g/h
E_i = Emission rate for test run, i, g/h
K_i = Test run weighting factor = $P_{i+1} - P_{i-1}$
n = Total number of test runs
P_i = Probability for burn rate during test run,i, obtained from Table 28-1, Part 2, E.P.A. Federal Register Volume 52, No. 32, page 5048

Test number	Burn rate kg/h,dry	Pi	Ei	Ki
11	0.67	0.121	5.34	0.300
12	0.89	0.300	3.77	0.629
13	1.48	0.750	2.98	0.682
14	2.91	0.982	2.38	0.250
				1.861

$$E = \frac{(5.34)(0.3)+(3.77)(0.629)+(2.97)(0.628)+(2.38)(0.250)}{1.861}$$

$$= \underline{3.54\ g/h}$$

A result of 3.54 g/h indicates how clean burning the heater is. Such a result is well within the E.P.A. heater emission limit of 7.5 g/h for July 1990 for a non-catalytic heater.
However, even with such good performance results there are some aspects of the heater which would need changing before production commenced. Such design alterations are listed and discussed below.

1. Baffle Plate Design.

It was suggested by one manufacter that the need for a replacable baffle plate may be necessary in case of burn-out. This information was primarily based on experience with conventional heaters that have the baffle plate situated inside the combustion chamber where it would get extremely hot. Temperature measurements made in the MKII indicated that this would be a less problem in this design. However if provisions were required to allow for baffle replacement, then one way to achieve this is illustrated in Figure 5.11. If the baffle needs replacing it would be a simple case of unbolting the old one and replacing it.

2. Ash Tray Door.

The MKII design has used the ash tray to collect ash and also serve as the door to the pedestal. With this setup it was difficult to achieve an air-tight seal. It is suggested that the ash tray and ash tray housing door be separate items. This door would also need to have an adjustable air intake for the start-up procedure as described in section 5.5.2. The ash tray should be placed inside the pedestal and be removed with a detachable handle.

3. Hopper Door

The hopper opening on the MKII design was sealed during operation using a large brick and a sheet of rock wool. After testing, a makeshift door was made up from 5mm plate and a heater door scavenged from a small heater. The result was a smaller opening at the top of the hopper as shown in Figure 5.12. This smaller opening has an advantage in that when the reloading the hopper, any volatiles in the hopper cavity are drawn down into the firebox more quickly than when the brick setup was used. This reduces the possibility of the volatiles igniting when the hopper entry is opened since they are removed quickly.

4. Construction Materials

The use of 5mm plate to build the heater might present a problem in the area surrounding the channel directing hot combustion gases from under the grate into the heat transfer section. This area is subjected to a great deal of heat and so it may be necessary to increase the thickness of the material used in this spot.

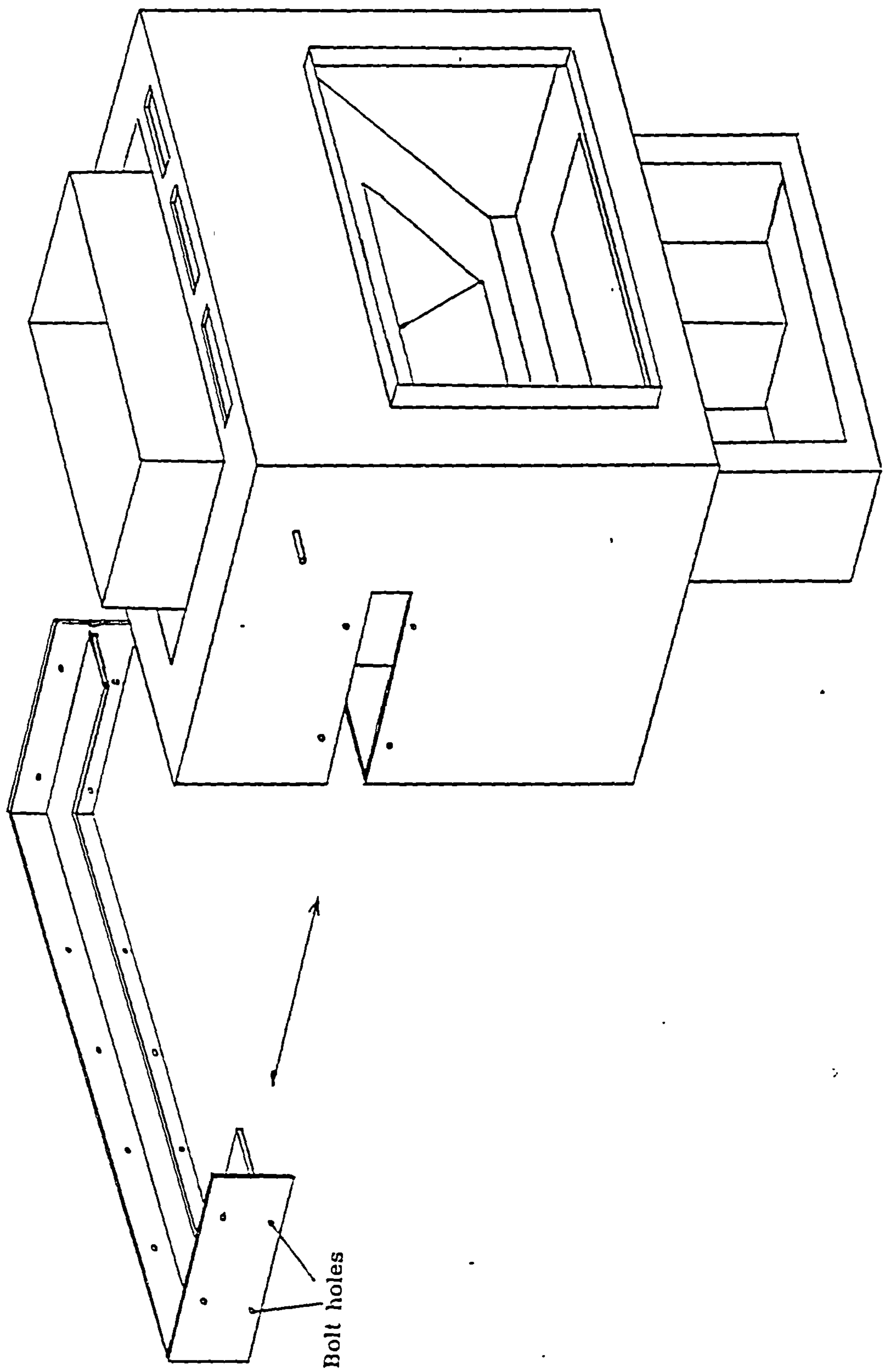
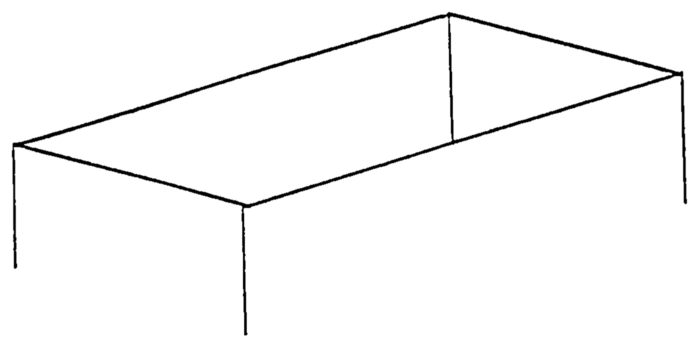
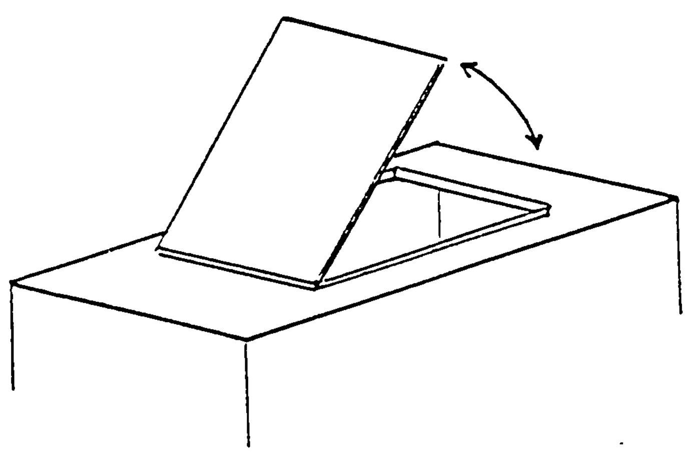


Figure 5.11. Suggested removable baffle design.



Hopper entrance with door.



Hopper entrance with door entrance now half the area.

Figure 5.12. Hopper door.

6 CONCLUSION

The aims of this research were twofold:

- to assess operation and performance of existing models of heaters when fuelled with briquettes of briquette/wood mixes; and

- to draw on the experience gained to design and test an improved model of a briquette burning heater.

Tests reported in the first four chapters were directed at assessing the safety aspects, creosote deposition, performance and emissions when burning wood or briquettes or a mix of the two in various existing heater designs.

Safety clearance testing carried out using the Australian Standard method set out in AS2918 demonstrated that the minimum safe clearance of some models of heater will be determined by briquette fuel use and some by wood fuel use. The difference in minimum safe clearance when either fuel is used may amount to 5 to 10 centimetres. The Australian Standard requires any heater which uses coal or briquettes to have clearance tests carried out with briquette fuel if reduced clearances are to be used. In light of these tests, this seems a sensible requirement.
Tests were carried out to see if adding briquettes to firewood resulted in any reduction of creosote formation in the heater flue. No difference in creosote formation was observed when burning either firewood or a mix of 50% wood and 50% briquettes, but only one model of heater was tested and no tests were carried out with wet firewood. The claims that mixing briquettes with wood decreased creosote formation could only be proved or disproved with more extensive testing.

The quantity and visibility of briquette ash (it is orange in colour) is greater than ash from firewood. Tests were carried out to see how much of this ash is carried out of the heater with the flue gas. On average, in one heater with updraft air, about 5% of the ash, or 2.8 g/h, was carried up the flue, but a factor of 10 variation was observed in just 3 tests. The significance of this on emissions warrants further testing.

The length of time a heater will burn on a single load of fuel was found to increase significantly if part or all of the fuel load was briquettes. A 60% increase in cycle time (time to burn a load of fuel) was achieved if the fuel load was all briquettes compared to all wood. The likelihood of a heater being able to burn overnight (8 hours unattended) is increased if part or all of the fuel load is briquettes.

Particulate emission measurements on the two heater models (one being updraft the other an 'S' draft) revealed greater emissions for the updraft model (36 g/h), compared to 32 g/h for the 'S' draft with briquettes (high burn rate). When a grate was added to the 'S' draft model, emissions were reduced to 5 g/h for briquettes. For both models, briquette emissions were 3 and 8 times greater than when wood was used in the updraft and 'S' draft respectively.

Performance results (gained from a total of 258 fuel loads) for the three models indicated that the presence of briquettes improved the efficiency of the updraft model by about 5 percentage points compared to wood. The other updraft heater had a leaking firebox and so the results were in doubt due to its erratic behavior. The 'S' draft heater's overall efficiency was about 3 percentage points lower when briquettes were used.

The power output for all models tested for performance decreased as the percentage of briquettes in the fuel load increased. The range of differences were 0.5 to 2 kW for the airtight updraft model and about 7kW for the 'S' draft heater.

The tests summarised above showed that existing heaters will burn briquettes, but conideration must be given to safety (installation) and in particular, emissions. There are many heaters available on the market and while most of them conform to basic design principles, small variations in their designs will most likely effect these two points.

While clearly there are more issues which could be investigated regarding the use of briquettes in existing residential heaters (for example, the effect of briquette combustion on firebox life), it was felt that the main ones had been addressed.

The heater design and tests reported in chapter 5 demonstrate that it is possible to develop a heater that will burn briquettes with high efficiency and produce low emissions.

By carefull analysis of the results obtained from the tests reported in chapters 1 to 4 and drawing from conclusions reported in the scientific literature, many of the problems identified in the first 4 chapters were avoided. As a result, the final heater design's performance matched or exceeded the objectives set out for the heater.

An overall efficiency of 60% was aimed for, the result obtained was 69%.

A power output range of 5 to 13kW was planned for, The heater produced a range of 3 to 16kW.

A single load burn time in excess of 15 hours was achieved. This was far above the chosen minimum of 8 hours.

Finally a weighted emission rate of 7.5g/h or less was easily accomplished with a 3.4g/h result.

Although the heater is still at the prototype stage, with the suggested improvements (section 5.6), mainly for operational ease, further development towards a production model is recommended. The merits of the heater's overall performance, compared to the existing heaters tested with briquettes, definitely highlights the heater's potential commercial viability.

7 REFERENCES

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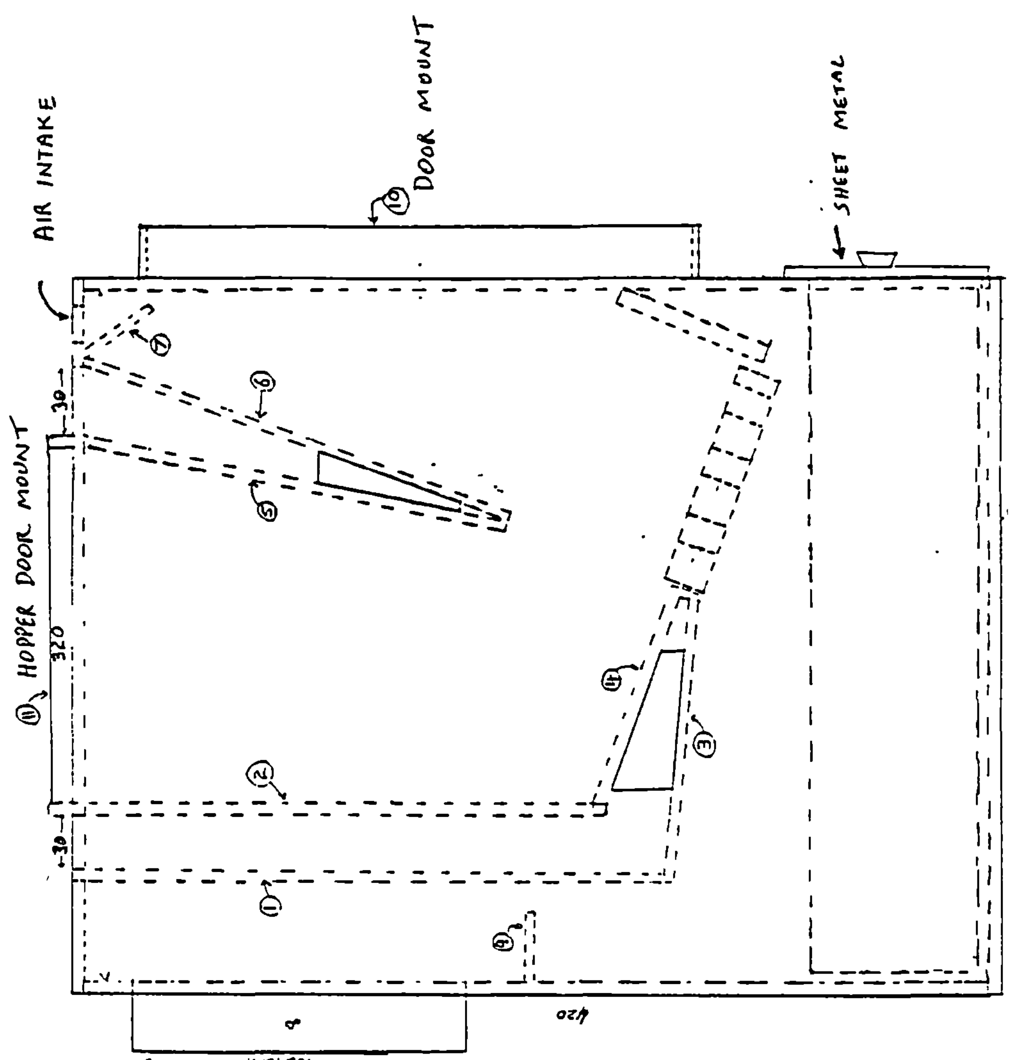
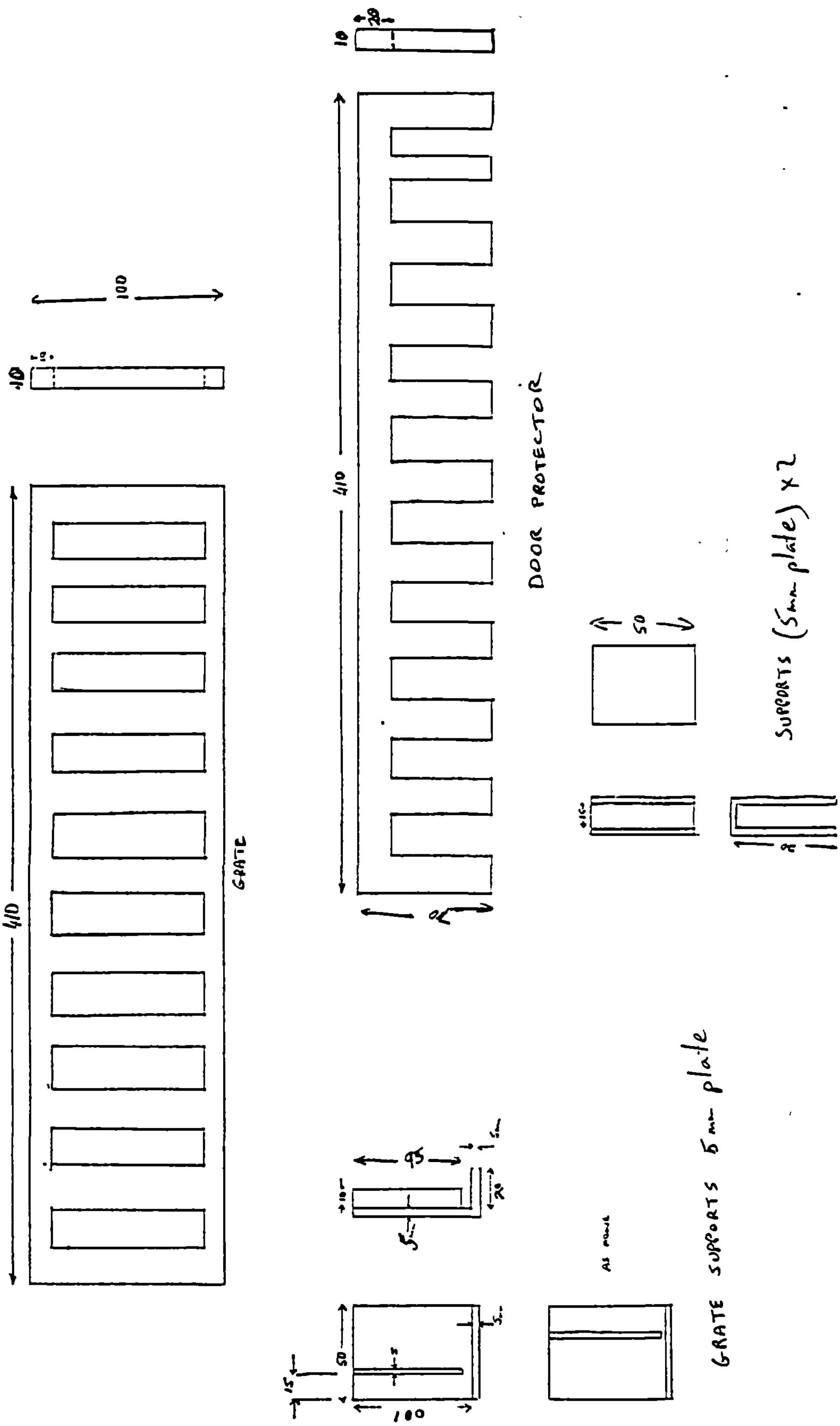
APPENDIX A

MKI CONSTRUCTION DRAWINGS

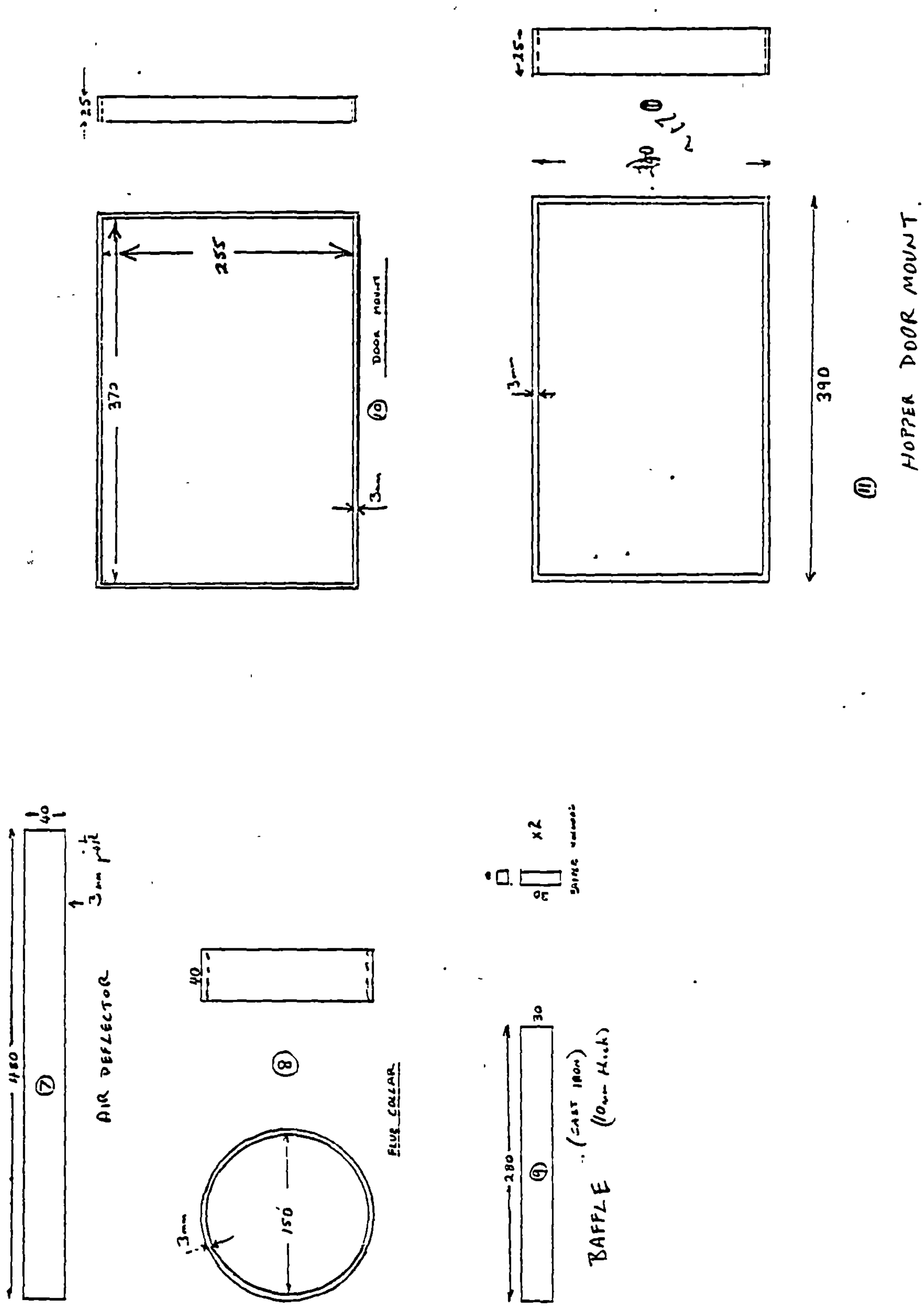
MKI SIDE VIEW



MKI GRATE


GRATE
410
100
DOOR PROTECTOR
SUPPORTS (5mm plate) x2
50
GRATE SUPPORTS 5mm plate
95
100
50
15

MKI ASSEMBLY PARTS



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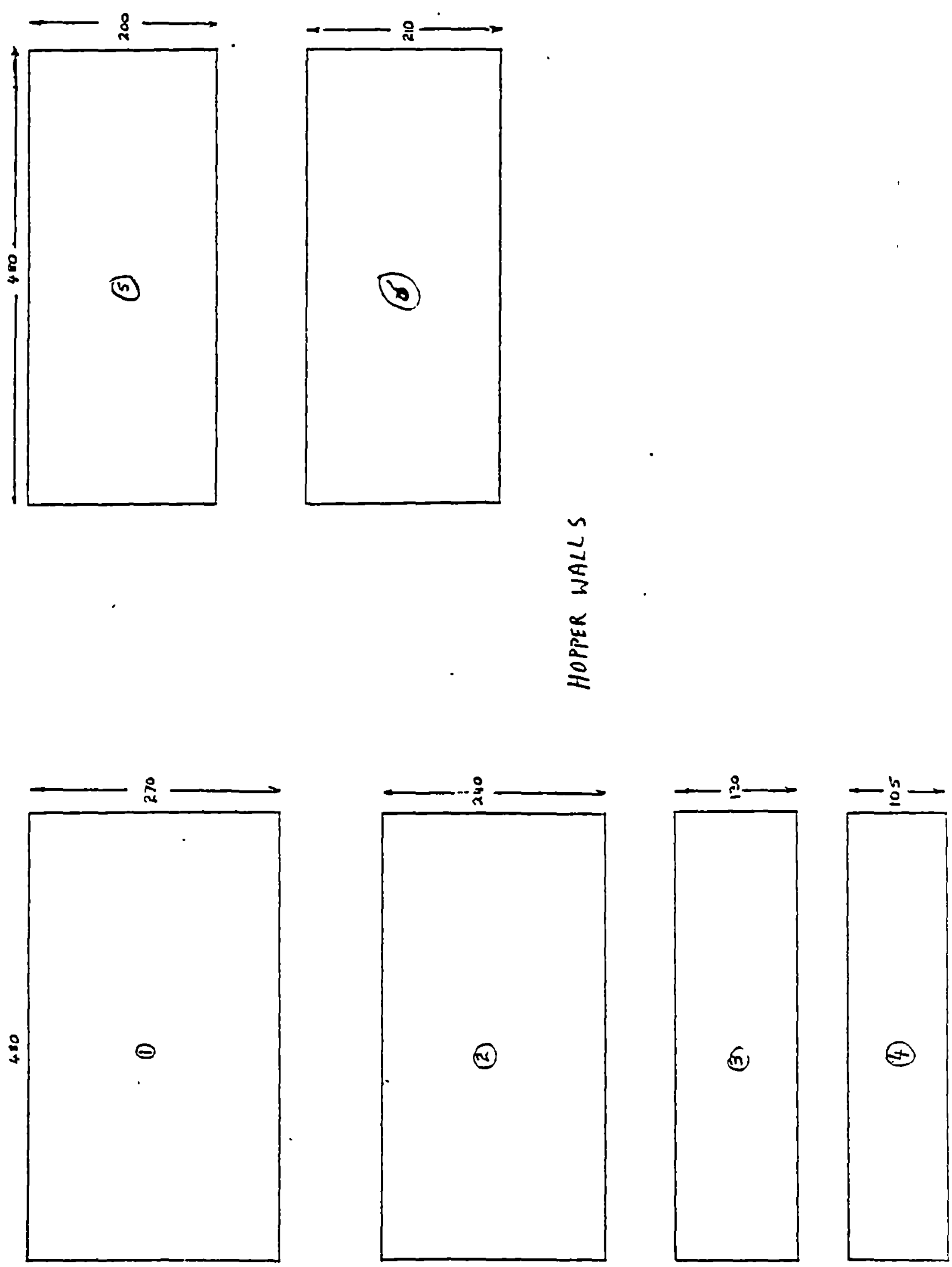
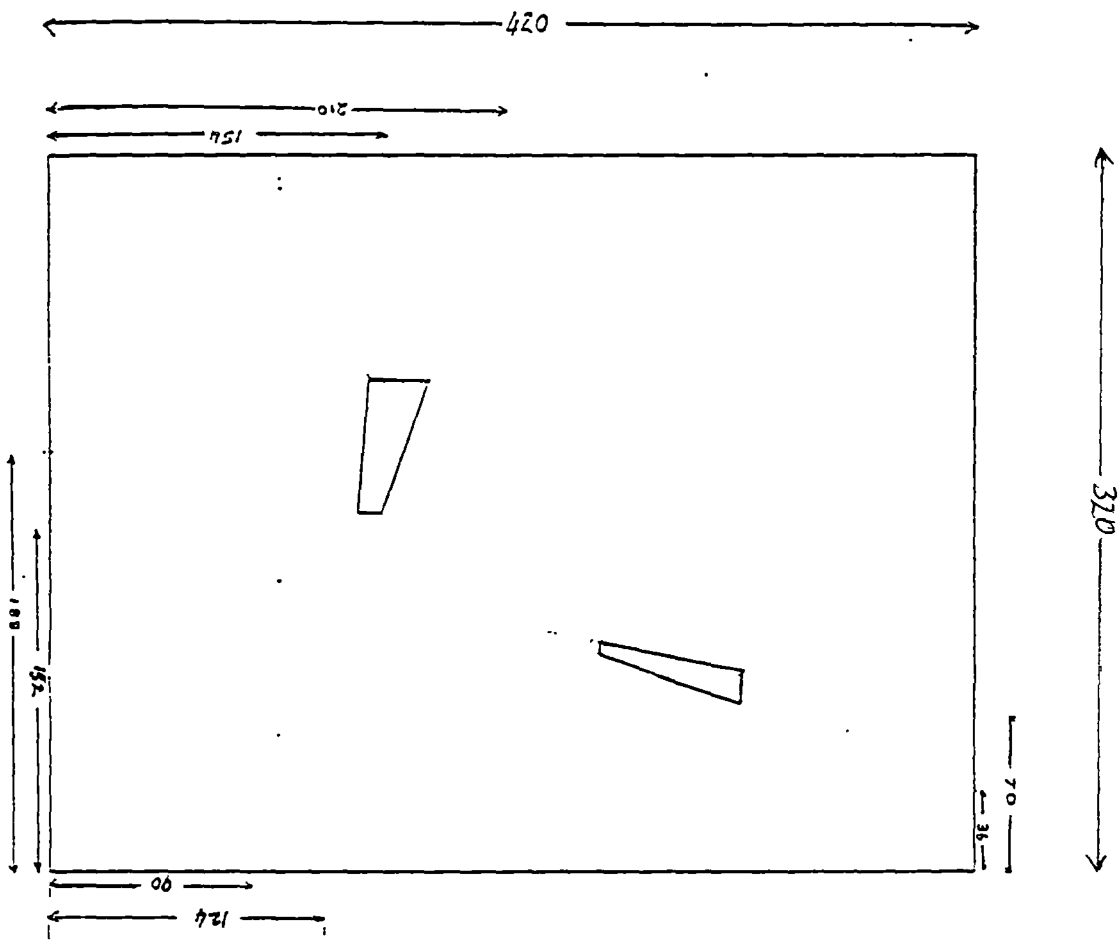
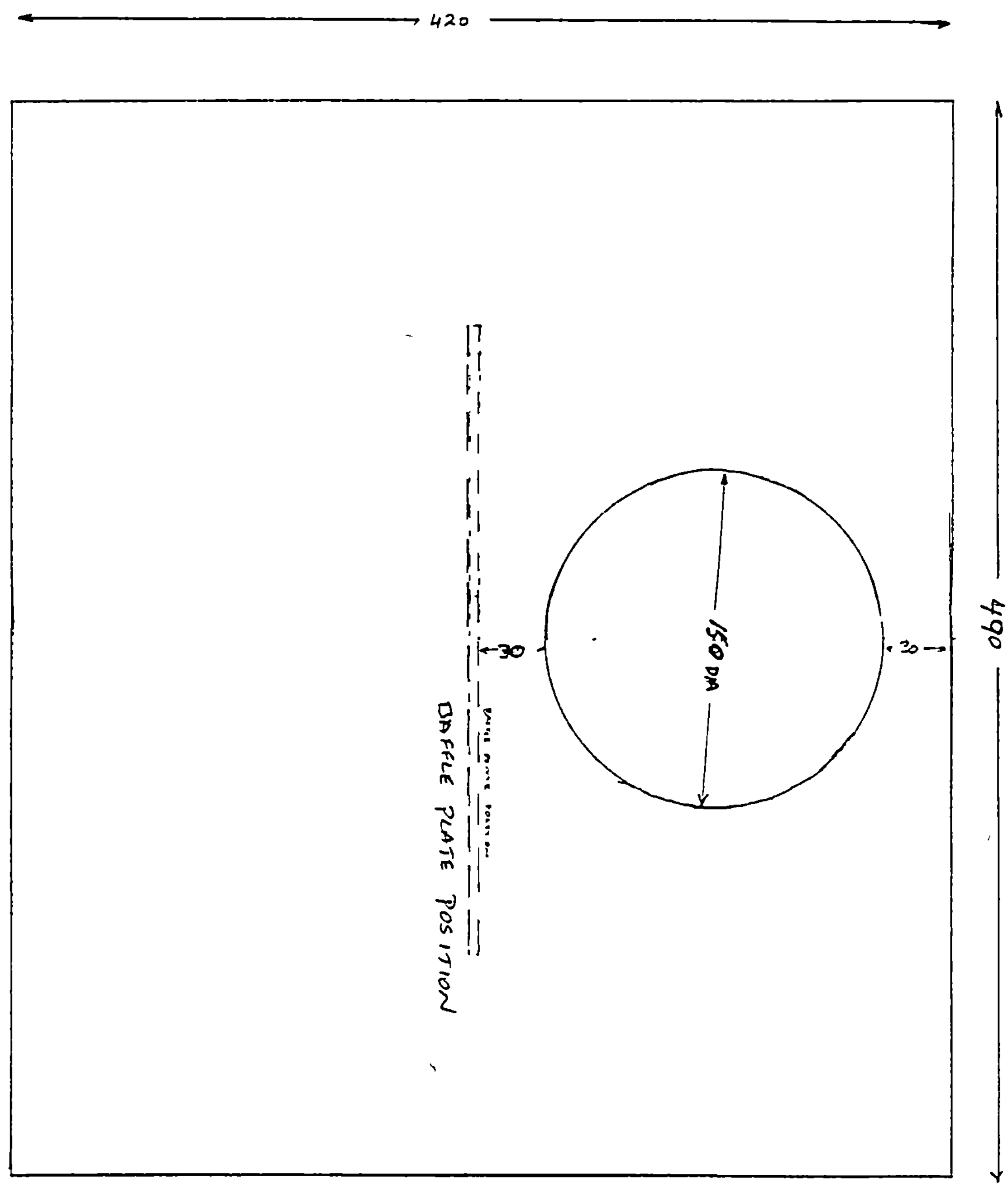


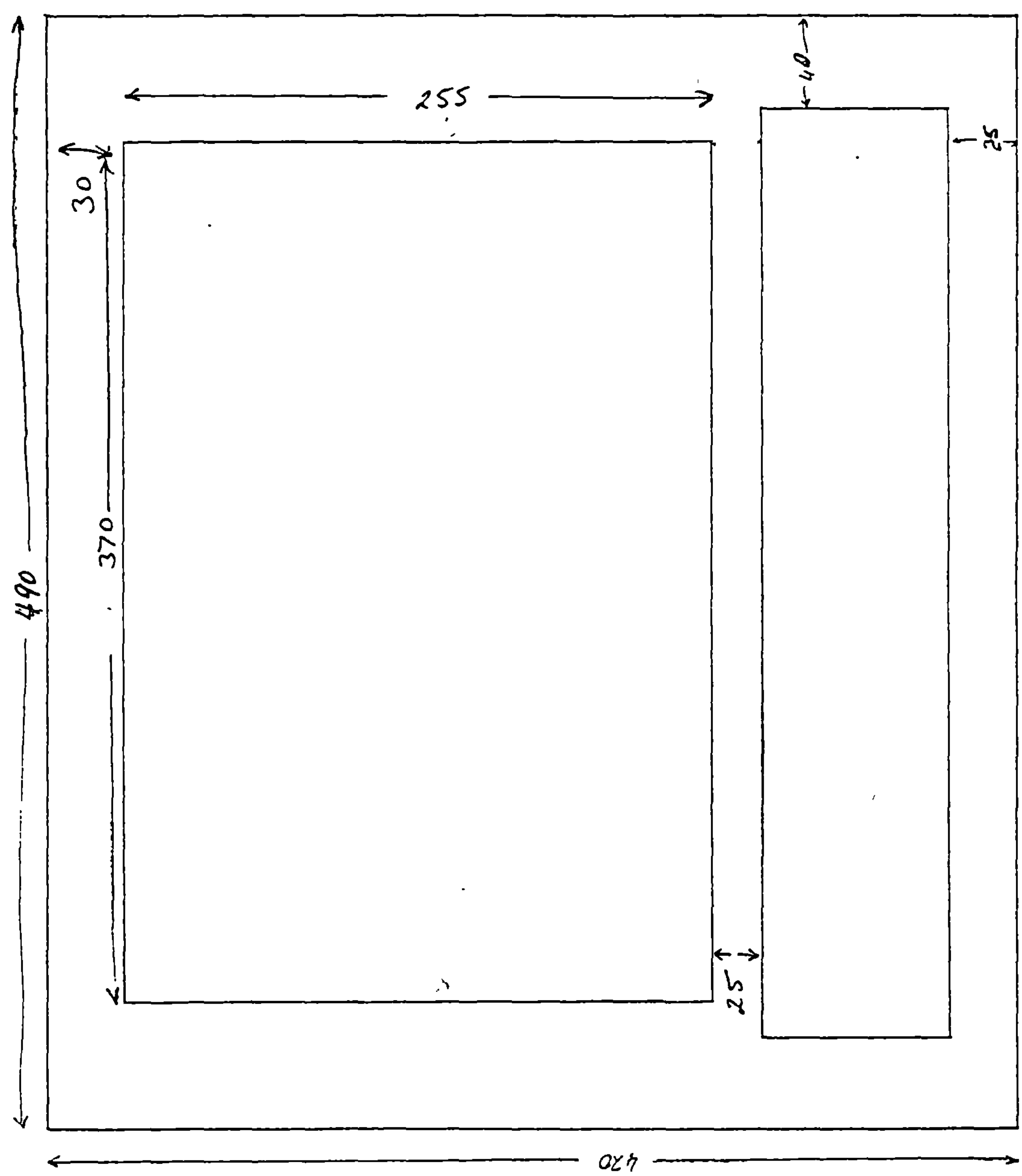
MKI SIDE WALLS



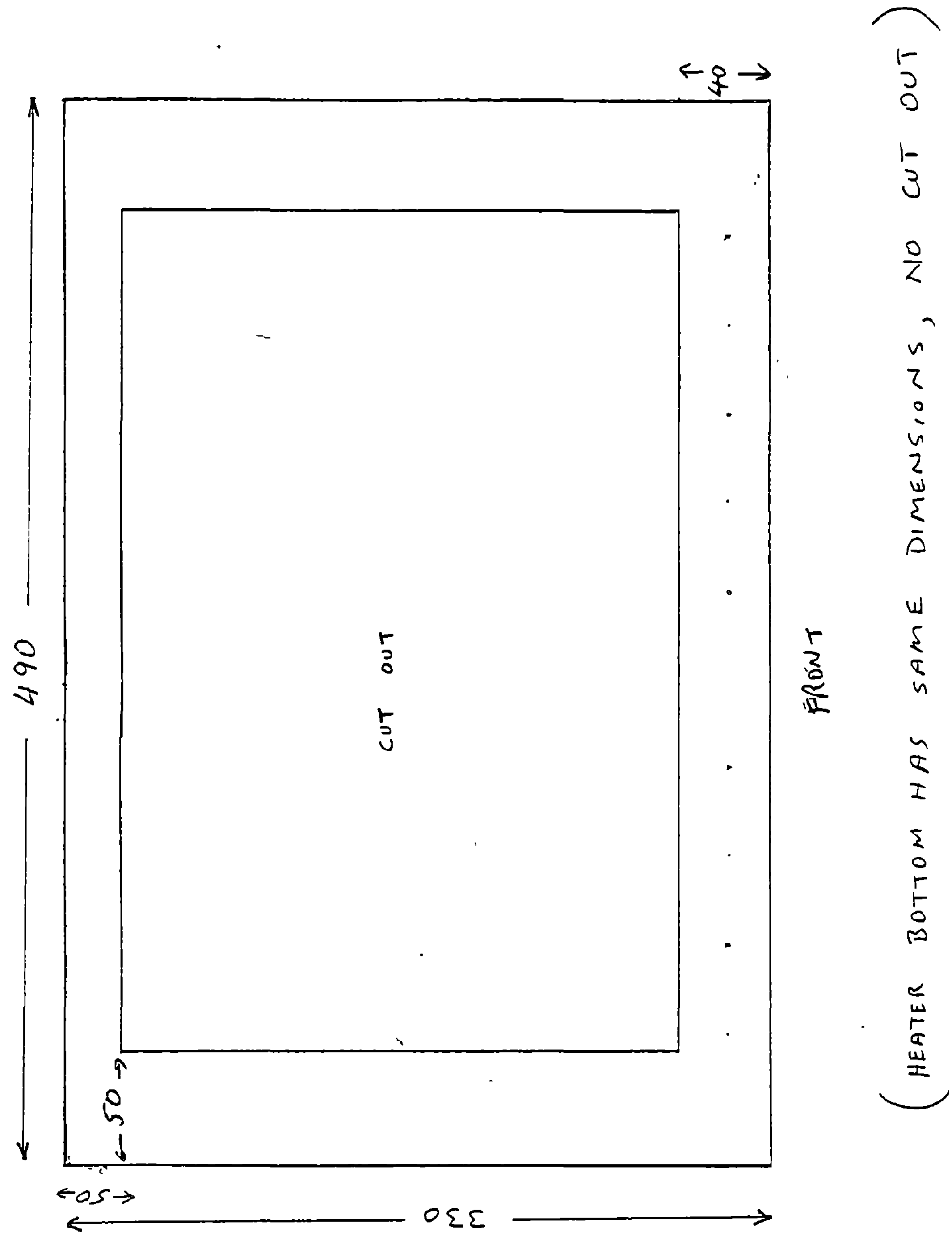
MKI REAR WALL



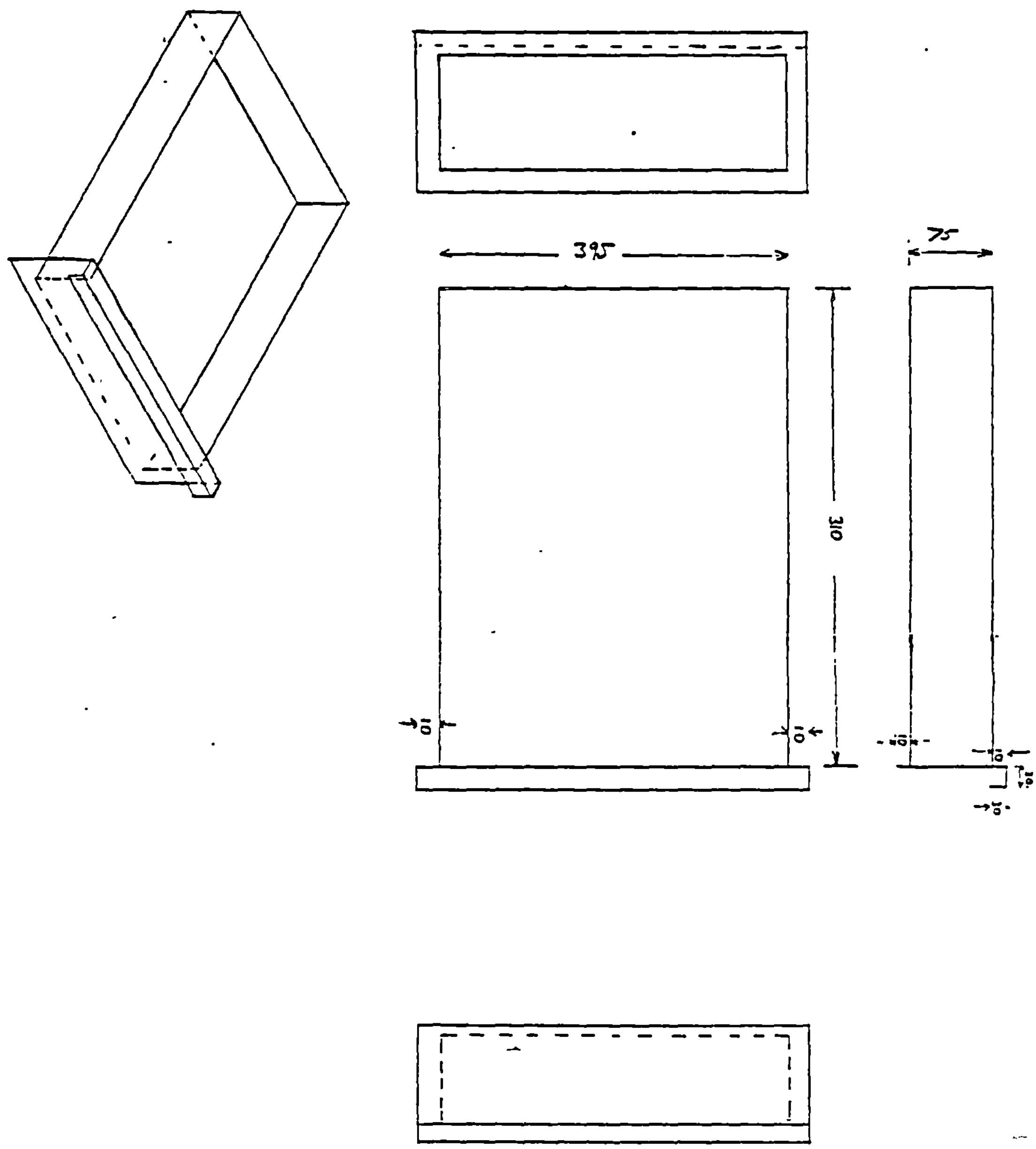
MKI FRONT WALL



MKI TOP SECTION



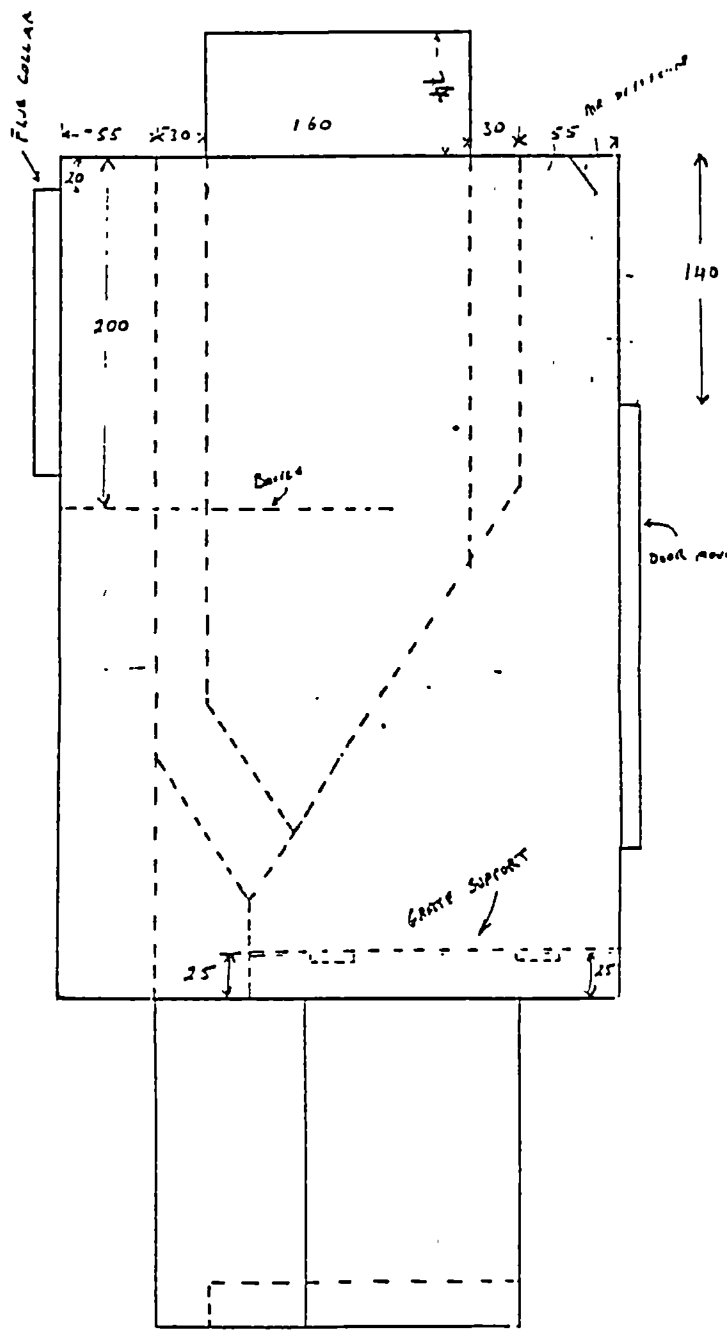
MKI ASH TRAY



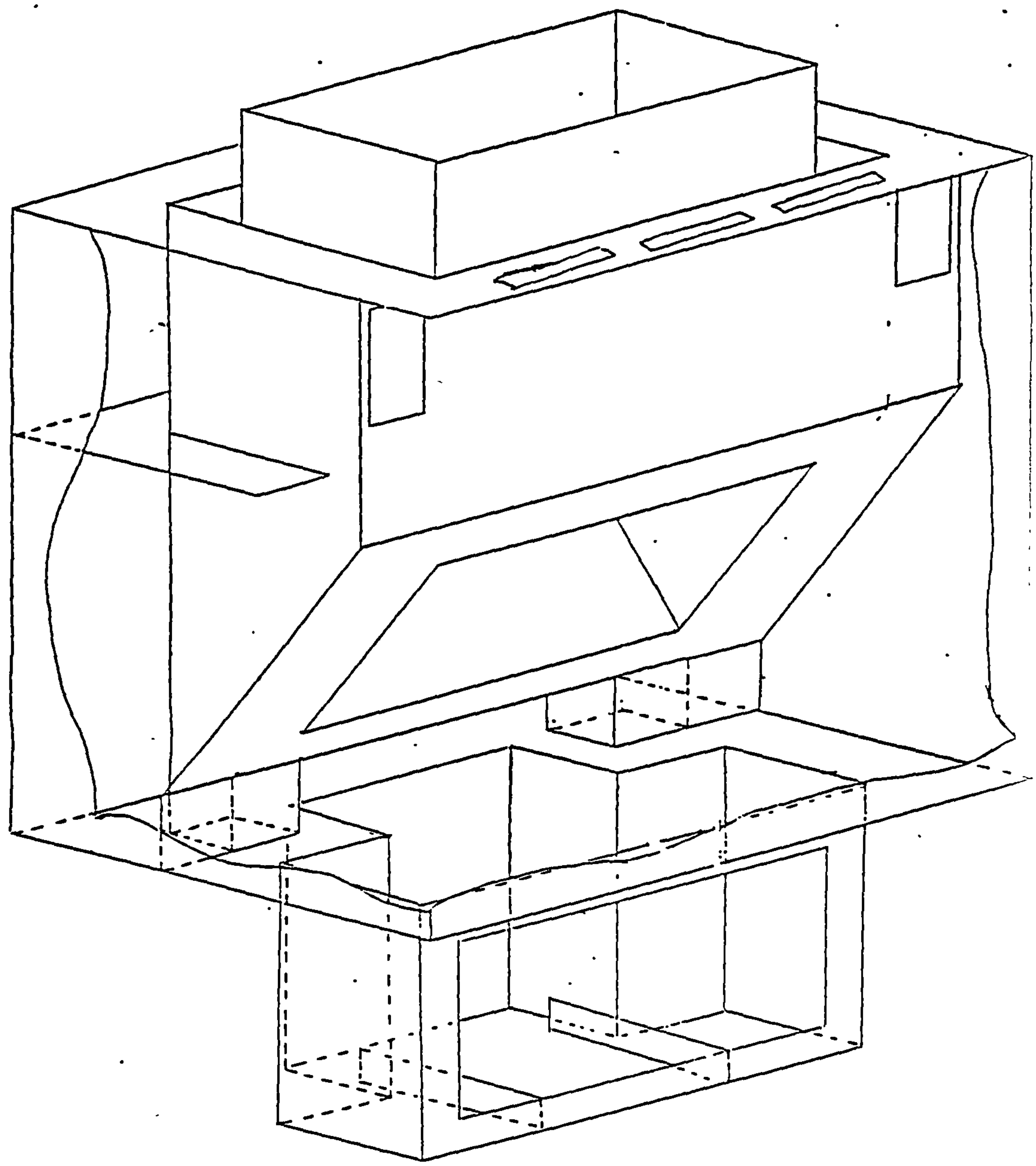
APPENDIX B

MKII CONSTRUCTION DRAWINGS

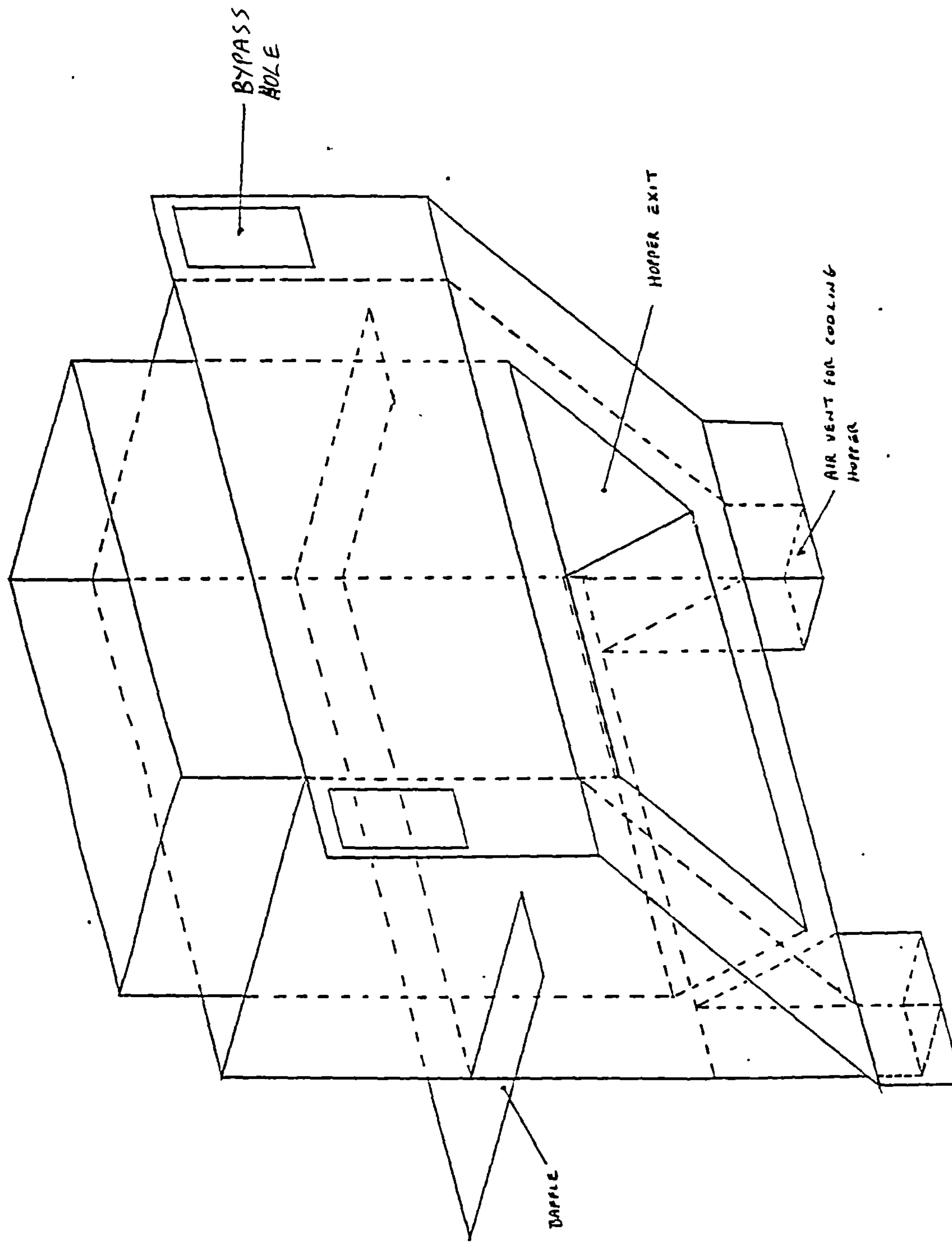
MKII SIDE VIEW



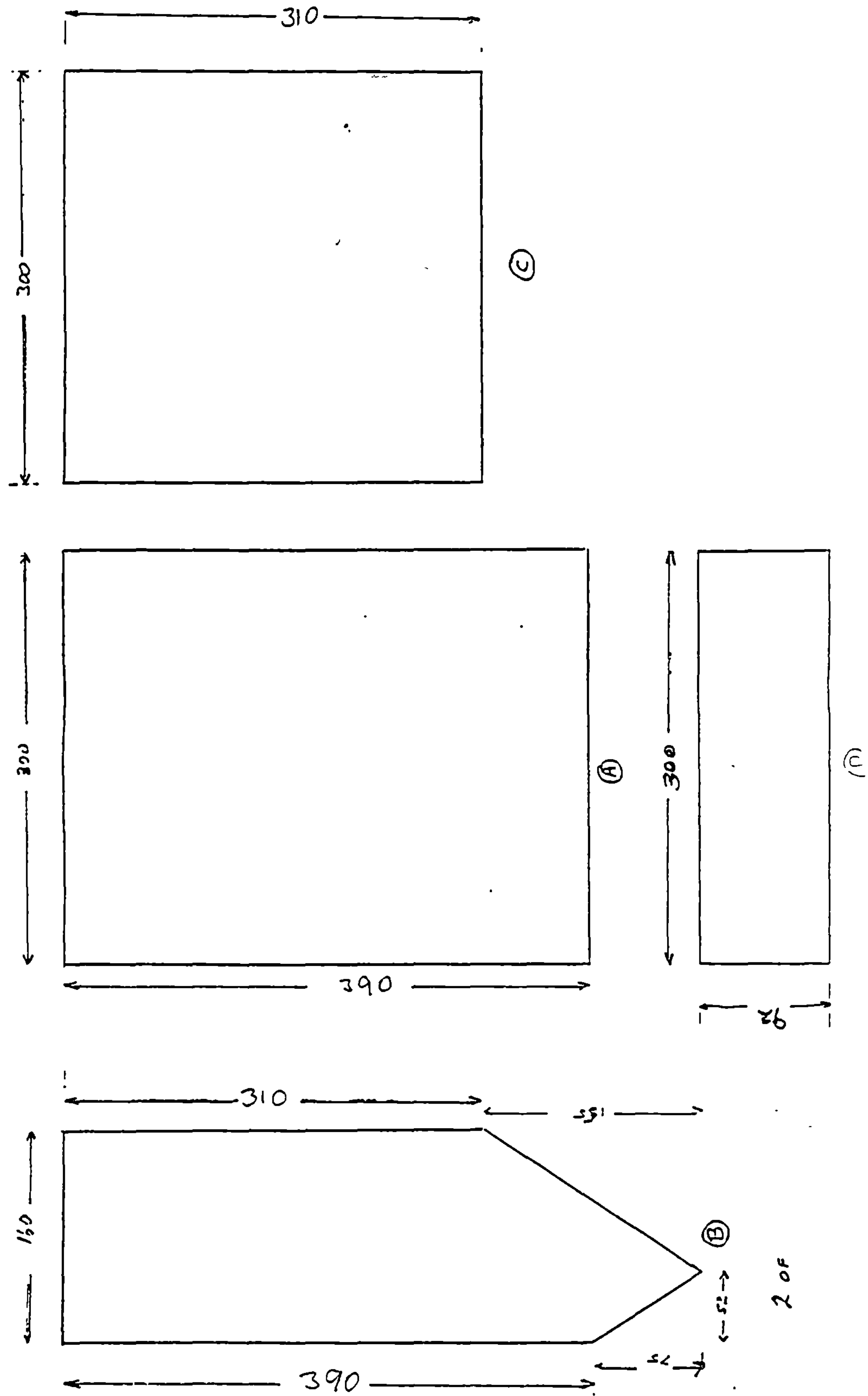
MKII CUT-AWAY SECTION
NO GRATE



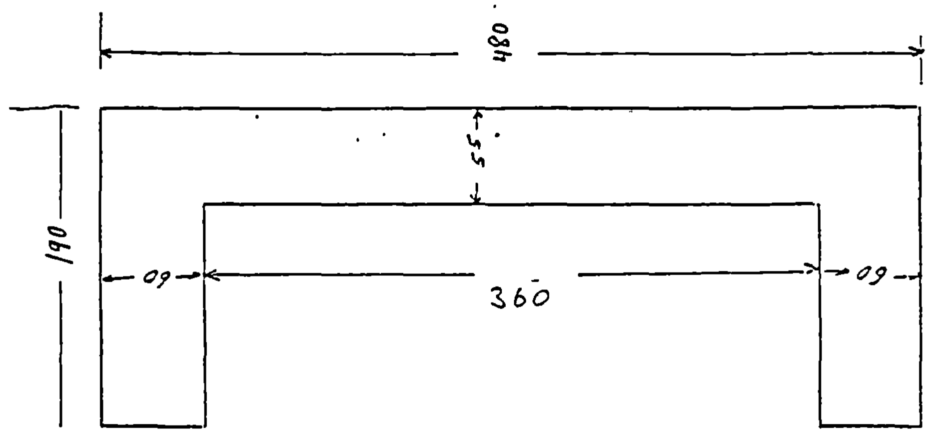
MKII DETAILED DRAWING OF HOPPER



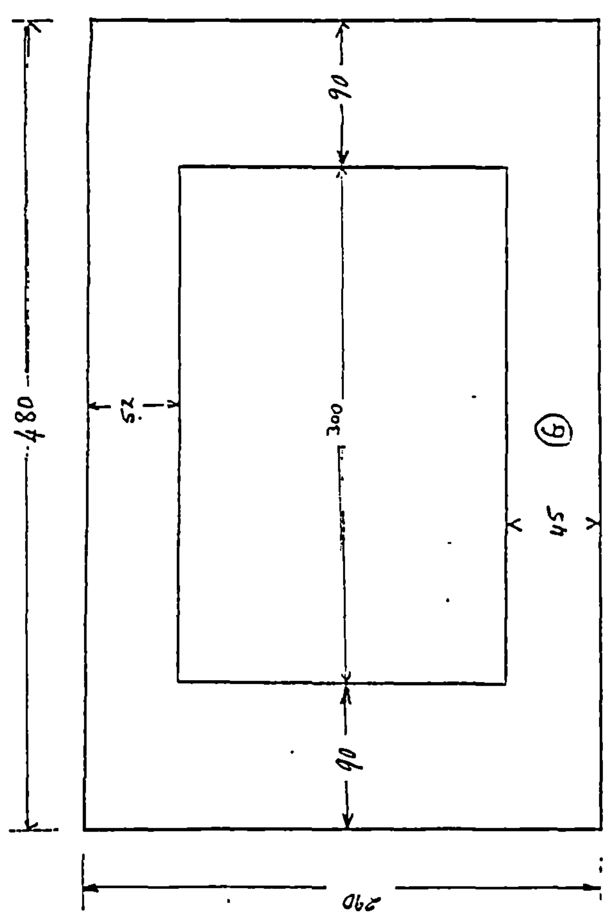
MKII HOPPER INNER SHELL
SECTIONS

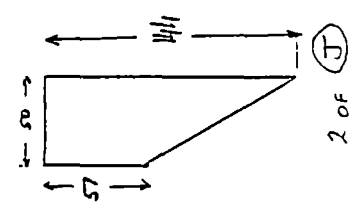


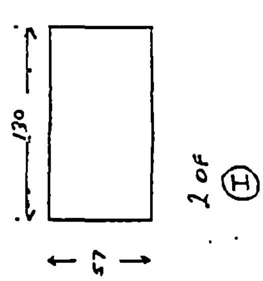
MKII HOPPER INNER SHELL
SECTIONS



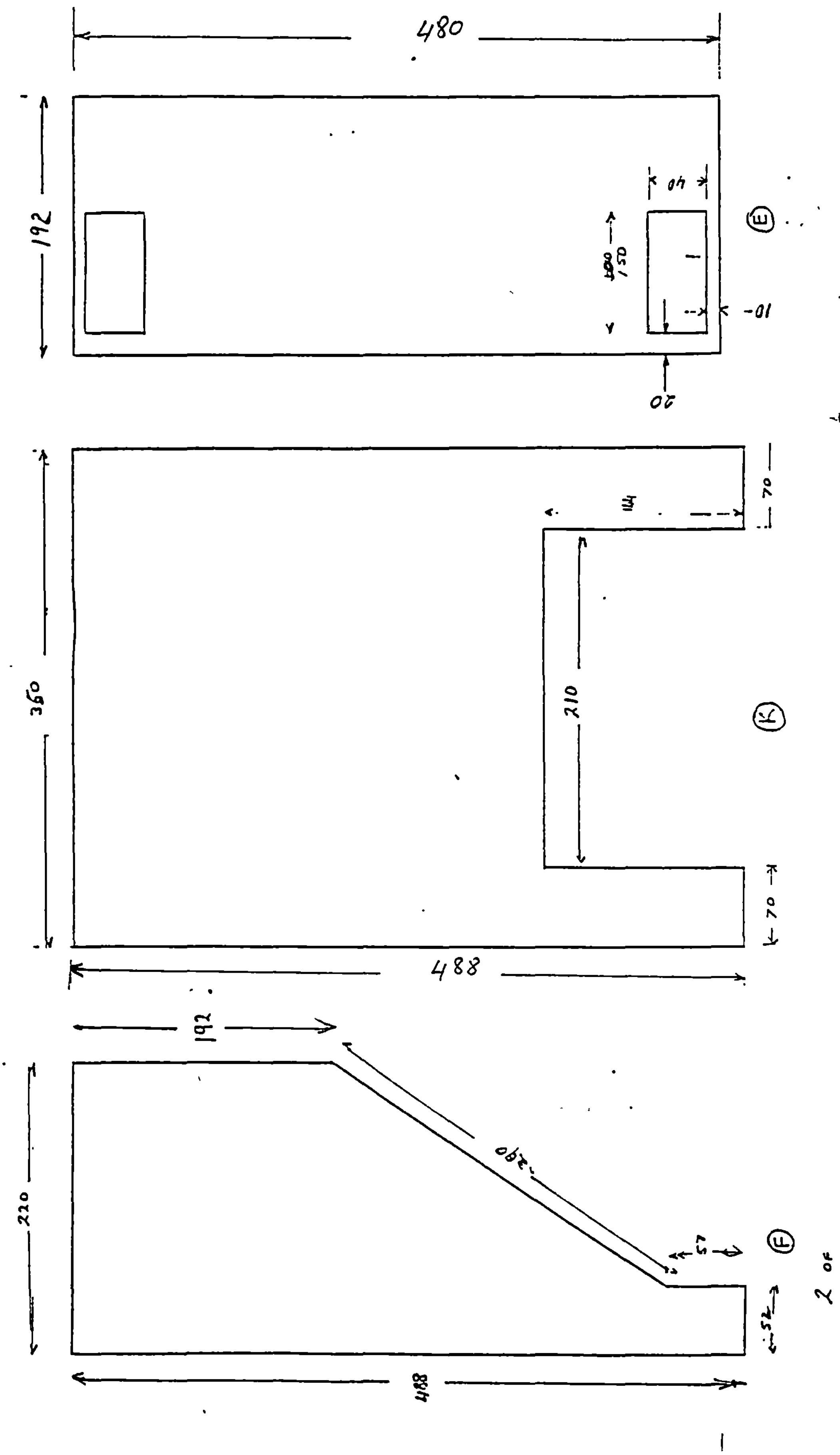
BAFFLE PLATE
(H)



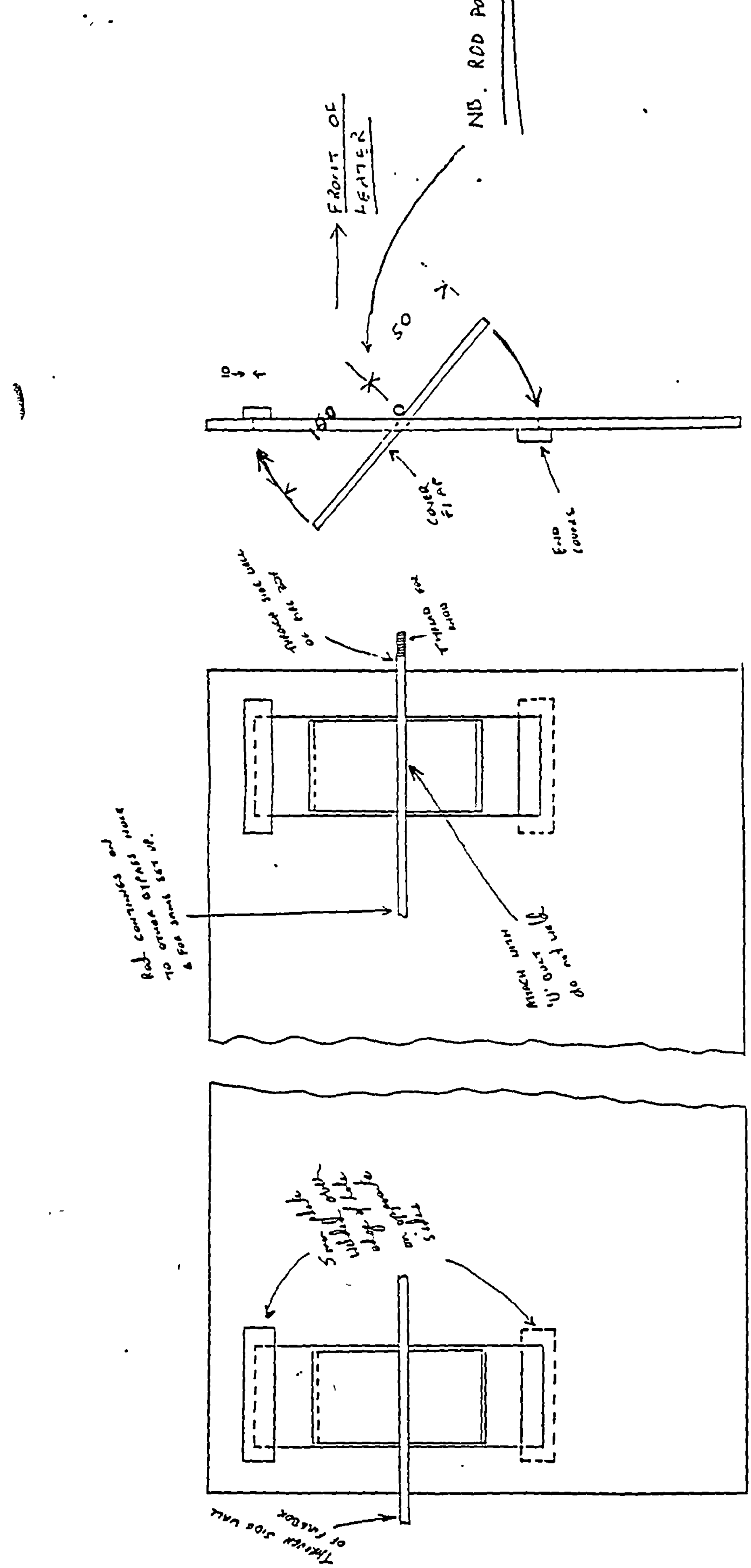




MKII HOPPER OUTER SHELL
SECTIONS

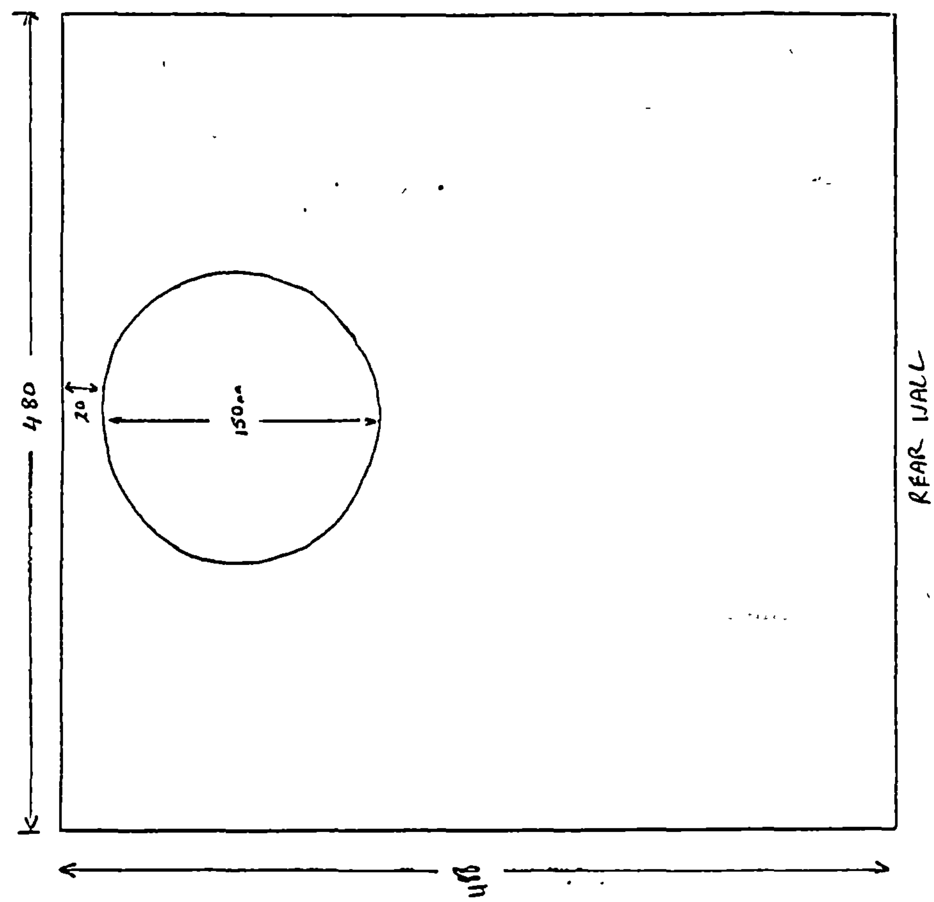


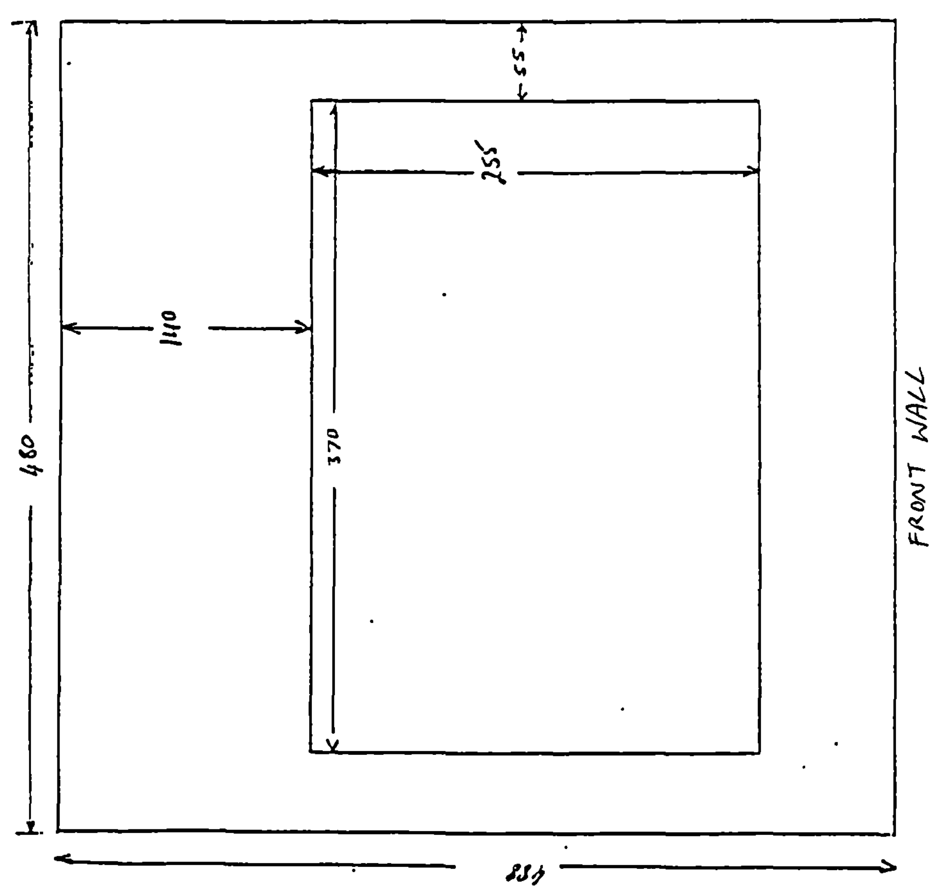
MKII DOWNDRAFT BYPASS SYSTEM



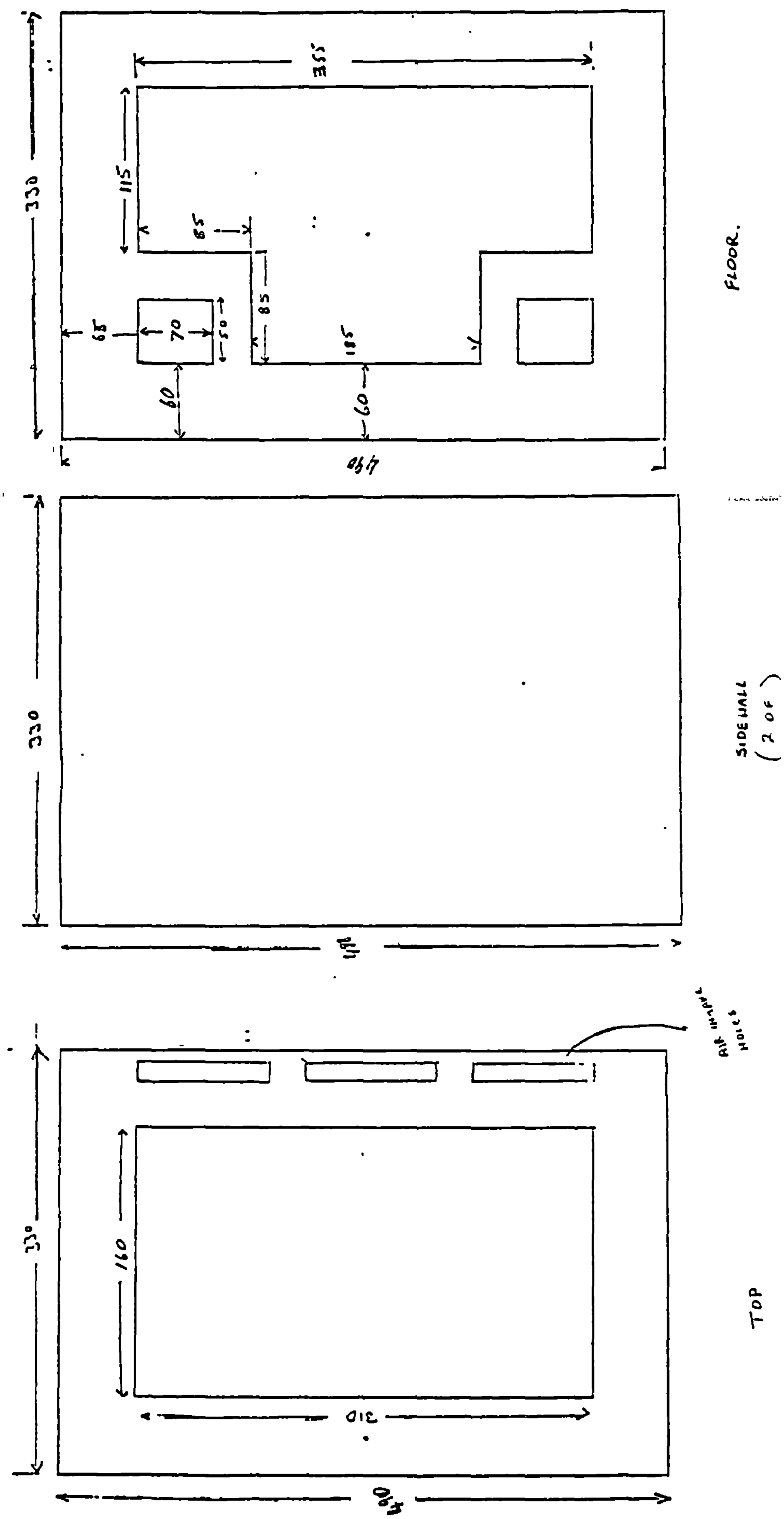
COVER FLAP x 2 = 38 x 145 mm
Rod = 10 mm (dia) x 590 mm long
END COVERS x 4 = 45 x 20 mm

MKII FIREBOX SECTIONS

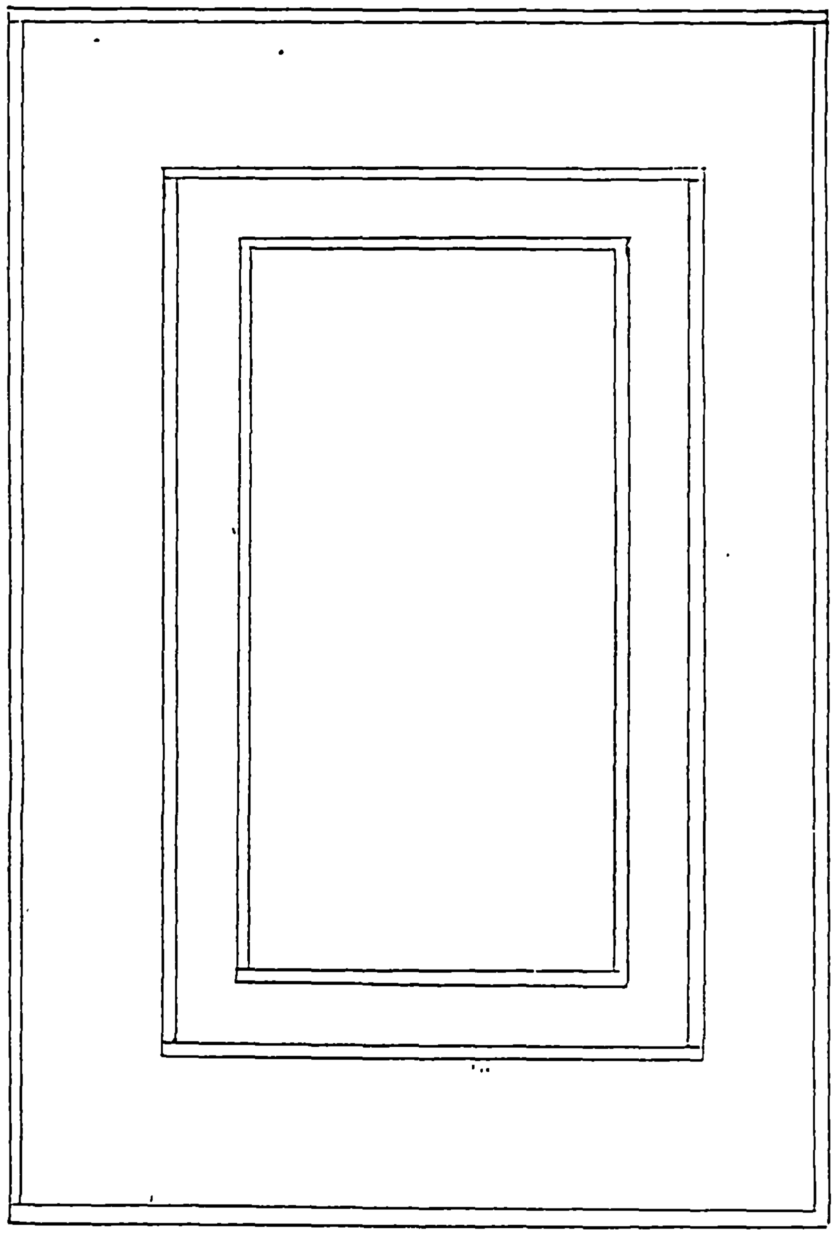




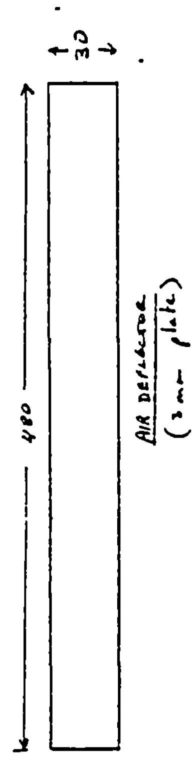
MKII FIREBOX SECTIONS

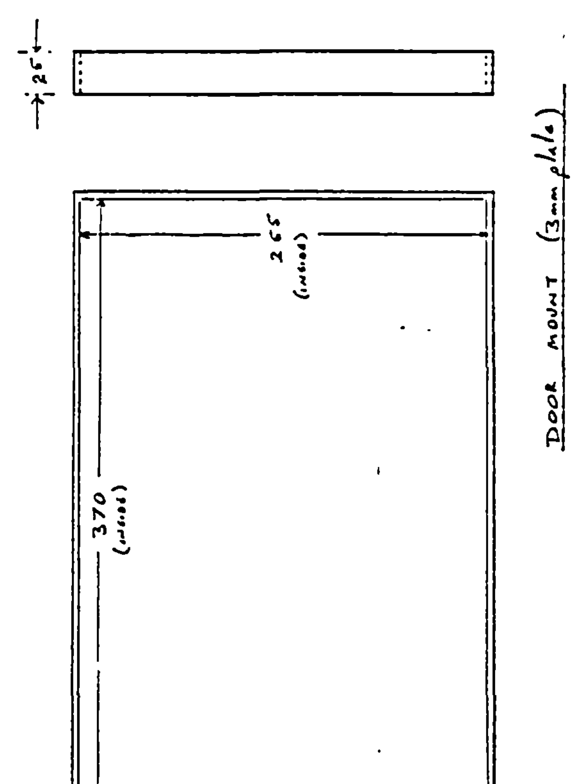


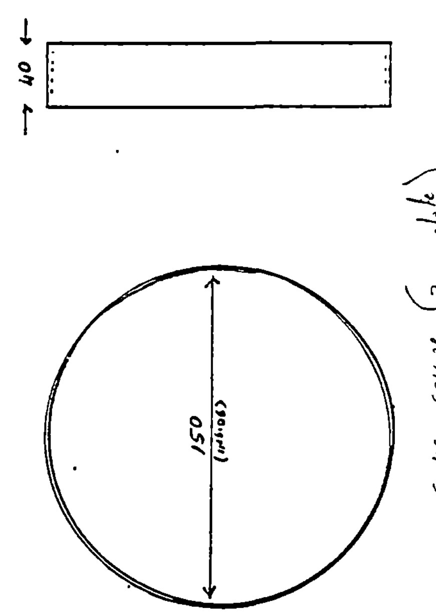
MKII PLAN ASSEMBLY



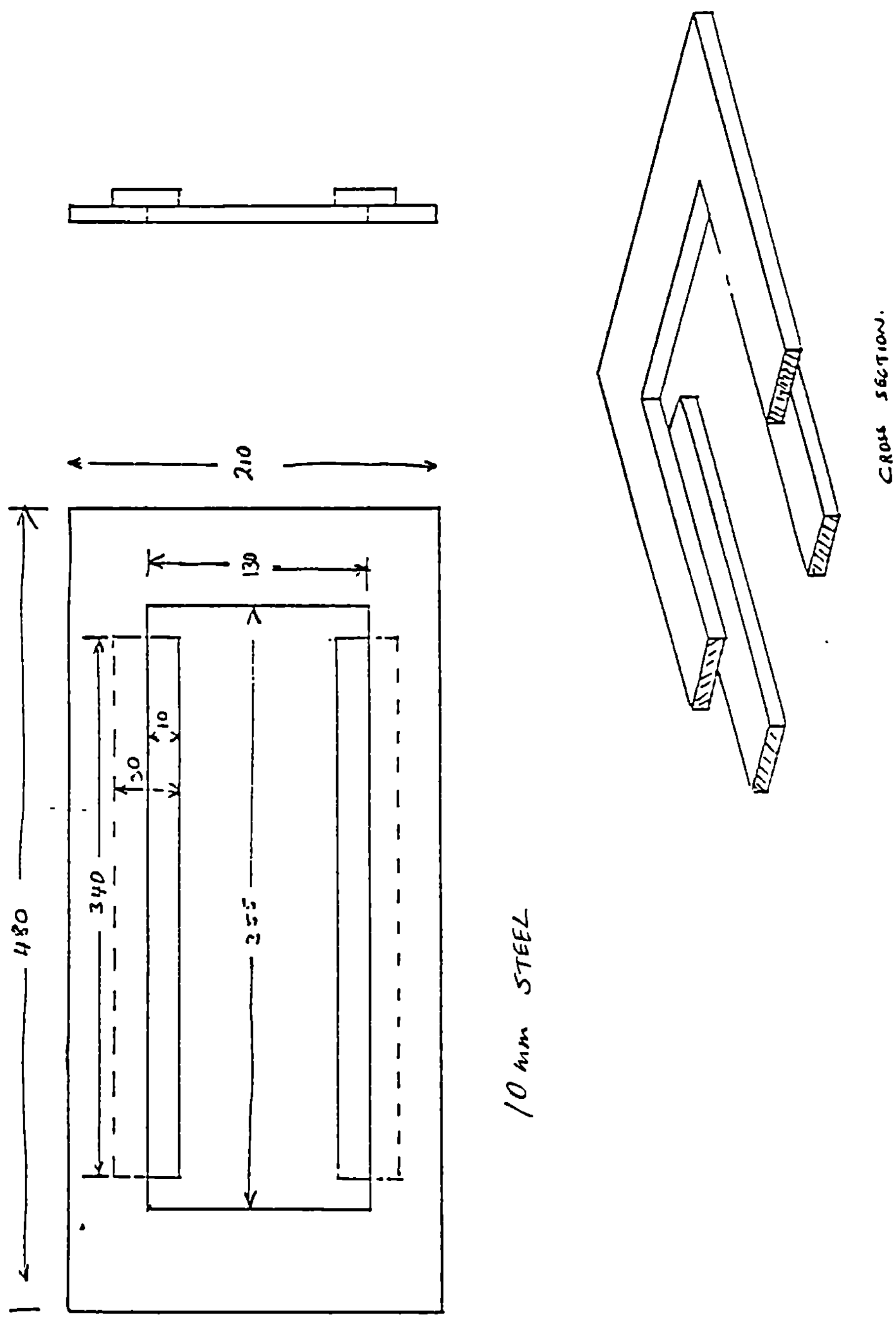
MKII ASSEMBLY SECTIONS



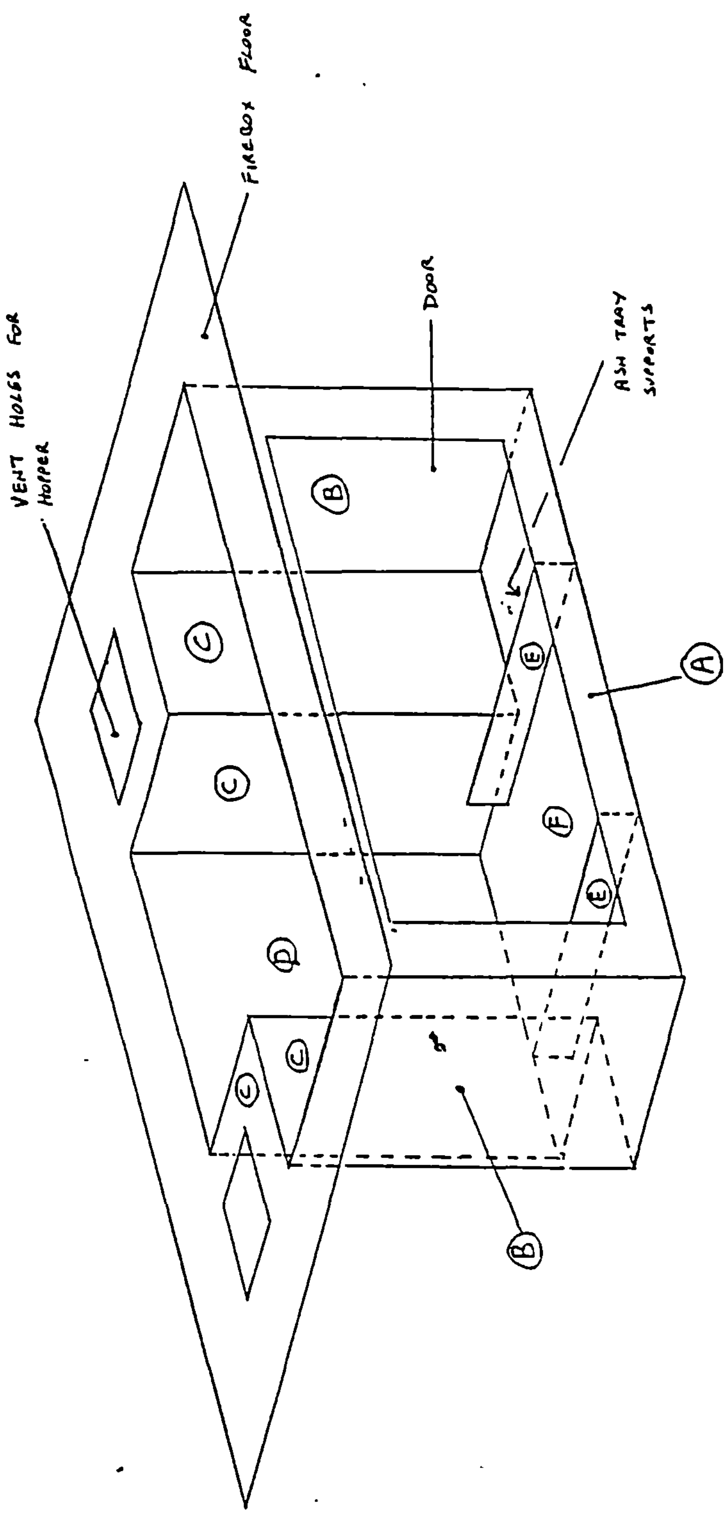




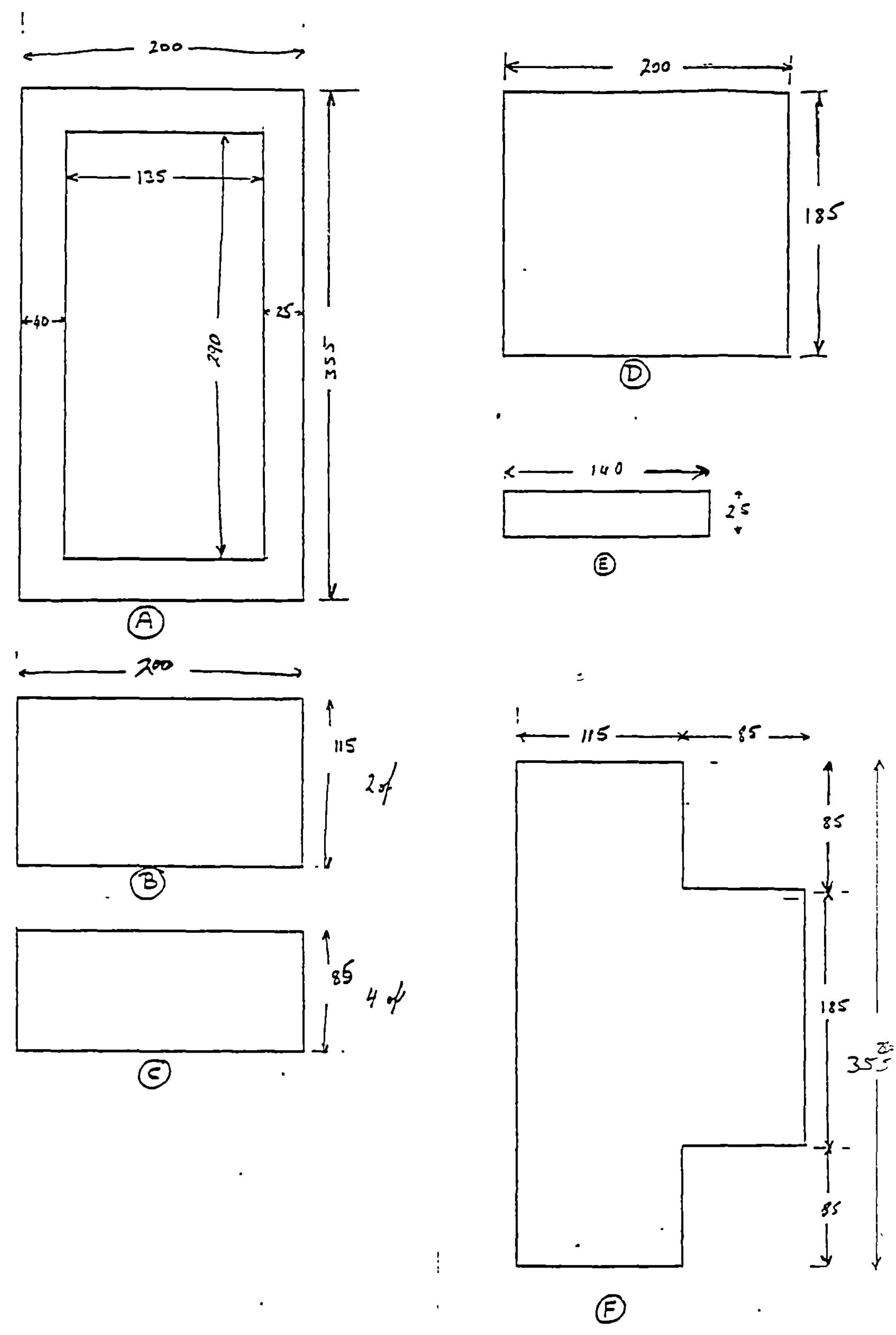
MKII GRATE SUPPORT



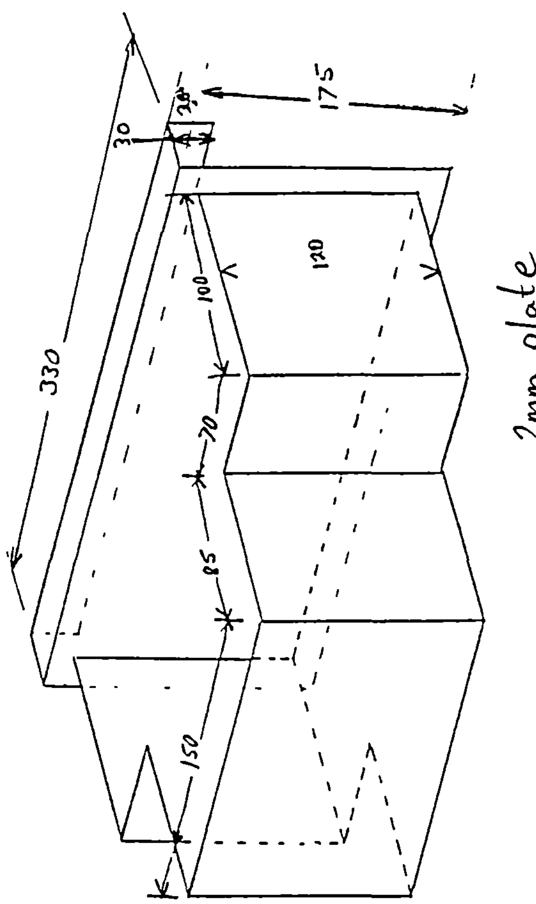
MKII FIREBOX FLOOR AND ASH TRAY LAYOUT



MKII ASH TRAY HOUSING



MKII ASH TRAY



APPENDIX C

MKII TEST PROCEDURES

TEST NUMBER 1

CALORIMETRY ROOM TEST SUMMARY

Efficiency and Emission rate tests were carried out on the MKII design at the Home Heating Laboratory on the 16/3/89.

FUEL: Briquettes.
Moisture: 15%.
Gross calorific value : 22.53 MJ/kg.

TEST DESCRIPTION

Air Intake Setting: HIGH

Heater Modifications: No secondary air. No firebricks. Fan on.

Test conditions:	Barometric Pressure mmHg	Relative Humidity %
	764	54

Test data:

Time	Scale (fuel wt.) kg	Power output kW	Comments
1100	-	0.00	The heater was ignited with firestarters.
1154	5.66	10.40	
1206	4.96	11.50	
1206	8.26	11.50	Reloaded the heater with 3.30kg
1220	7.10	11.60	
1350	2.00/10.12	13.00	Heater was reloaded with a 8.12kg cycle load. Base weight for test was 2.00kg.
1408	9.06	12.00	
1442	7.00	11.10	
1516	5.04	11.80	
1540	4.00	12.60	
1624	2.12	11.70	
1630	2.00	11.40	End of cycle and test.

OVERALL TEST CYCLE SUMMARY

Average power = 12.04kW
Overall efficiency = 62.4%
Burn rate = 3.06kg/h (wet)
2.60kg/h (dry).
Emissions = 8.59g/h

TEST NUMBER 2

CALORIMETRY ROOM TEST SUMMARY

Efficiency and Emission rate tests were carried out on the MKII design at the Home Heating Laboratory on the 20/3/89.

FUEL: Briquettes.
Moisture: 15%.
Gross calorific value : 22.53 MJ/kg.

TEST DESCRIPTION

Air Intake Setting: HIGH

Heater Modifications: No secondary air. No firebricks. Fan on.

Test conditions:

Barometric Pressure mmHg	Relative Humidity %
767	70

Test data:

Time	Scale (fuel wt.) kg	Power output kW	Comments
1146	12.70	0.00	The heater was ignited with firestarters.
1220	10.70	3.32	
1410	2.08/10.96	15.7	Using a base weight of 2.08kg and a cycle load of 8.88kg the test cycle commenced.
1442	8.20	15.1	
1516	5.18	17.6	
1542	3.52	18.2	
1608	2.42	16.0	
1620	2.08	15.2	End of cycle and test.

OVERALL TEST CYCLE SUMMARY

Average power = 16.57kW
Overall efficiency = 64.6%
Burn rate = 4.10kg/h (wet)
3.49kg/h (dry).
Emissions = 6.99g/h

TEST NUMBER 3

CALORIMETRY ROOM TEST SUMMARY

Efficiency and Emission rate tests were carried out on the MKII design at the Home Heating Laboratory on the 21/3/89.

FUEL: Briquettes.
Moisture: 15%.
Gross calorific value : 22.53 MJ/kg.

TEST DESCRIPTION

Air Intake Setting: HIGH

Heater Modifications: No secondary air. No firebricks. Fan on.

Test conditions:	Barometric Pressure mmHg	Relative Humidity %
	762	65

Test data:

Time	Scale (fuel wt.) kg	Power output kW	Comments
1100	4.00	0.00	The heater was ignited with firestarters.
1142	10.32	2.00	Hopper reloaded
1404	0.86/3.80	11.2	Hopper reloaded with 3kg of briquettes and the fan turned on.
1426	2.10/9.50	14.00	Test cycle commenced with a base weight of 2.10kg and a cycle load of 7.40kg.
1458	7.10	12.20	
1530	4.60	16.60	
1558	2.66	18.00	
16716	2.10	16.40	End of cycle and test.

OVERALL TEST CYCLE SUMMARY

Average power = 15.00kW
Overall efficiency = 59.4%
Burn rate = 4.04kg/h (wet)
3.43kg/h (dry).
Emissions = 4.28g/h

TEST NUMBER 4

CALORIMETRY ROOM TEST SUMMARY

Efficiency and Emission rate tests were carried out on the MKII design at the Home Heating Laboratory on the 22/3/89.

FUEL: Briquettes.
Moisture: 15%.
Gross calorific value : 22.53 MJ/kg.

TEST DESCRIPTION

Air Intake Setting: MEDIUM

Heater Modifications: No secondary air. No firebricks. Fan on.

Test conditions:	Barometric Pressure mmHg	Relative Humidity %
	758	65

Test data:

Time	Scale (fuel wt.) kg	Power output kW	Comments
1028	3.60	0.00	The heater was ignited with firestarters.
1134	1.90/6.66	8.02	Reloaded heater with 4.76kg of briquettes and turned intake down.
1338	2.54	5.99	
1342	8.82	5.75	Test cycle started with 6.28kg of fuel and a base weight of 2.54kg.
1412	7.00	8.57	
1444	5.26	9.19	
1512	4.42	8.60	
1542	3.76	7.96	
1632	3.32	7.92	
1702	2.54	7.31	End of cycle and test.

OVERALL TEST CYCLE SUMMARY

Average power = 8.10kW
Overall efficiency = 68.7%
Burn rate = 1.88kg/h (wet)
1.60kg/h (dry).
Emissions = 4.29g/h

TEST NUMBER 5

CALORIMETRY ROOM TEST SUMMARY

Efficiency and heat output tests were carried out on the MKII design at the Home Heating Laboratory on the 1/5/89.

FUEL: Briquettes.
Moisture: 15%.
Gross calorific value : 22.53 MJ/kg.

TEST DESCRIPTION

Air Intake Setting: HIGH

Heater Modifications: Secondary air at hopper exit. No firebricks. Fan on.

Test conditions:	Barometric Pressure mmHg	Relative Humidity %
	764	80

Test data:

Time	Scale (fuel wt.) kg	Power output kW	Comments
1040	5.70	0.00	The heater was ignited with this fuel weight and several firestarters. The heater was in up-draught mode.
1106	15.02	2.24	The heater was switched to the down-draught mode and the hopper filled with fuel.
1152	10.24	9.09	The convection fan was turned on.
1210	8.68	12.80	
1320	2.94	18.30	
1338	2.30 12.24	16.80	The weight of 2.30kg was taken as the base weight of the test. The test cycle load was 9.94kg, giving a total weight at the start as 12.24kg.
1402	9.80	15.10	
1422	8.20	15.20	
1548	2.92	16.20	
1608	2.30	14.50	The return to the base weight of 2.30kg indicated the end of the cycle and the end of the test.

OVERALL TEST CYCLE SUMMARY

Average power = 16.28kW
Overall efficiency = 65.4%
Burn rate = 3.98kg/h (wet)
3.38kg/h (dry).

TEST NUMBER 6

CALORIMETRY ROOM TEST SUMMARY

Efficiency and Emission rate tests were carried out on the MKII design at the Home Heating Laboratory on the 2/5/89.

FUEL: Briquettes.
Moisture: 15%.
Gross calorific value : 22.53 MJ/kg.

TEST DESCRIPTION

Air Intake Setting: HIGH

Heater Modifications: Secondary air at hopper exit. No firebricks. Fan on.

Test conditions:	Barometric Pressure mmHg	Relative Humidity %
	760	70

Test data:

Time	Scale (fuel wt.) kg	Power output kW	Comments
1000	-	0.00	The heater was ignited with a full hopper.
1306	1.80	15.30	At this point the test cycle began. A weight
1306	11.18	15.3	9.336kg of briquettes was used for the test. This gave a combined fuel weight of 11.16kg.
1324	9.68	13.6	
1332	8.94	13.5	
1346	7.72	14.30	
1432	4.08	17.40	
1500	2.64	16.30	
1532	1.80	13.50	This was the end of the cycle and test.

OVERALL TEST CYCLE SUMMARY

Average power = 15.50kW
Overall efficiency = 64.4%
Burn rate = 3.85kg/h (wet)
3.27kg/h (dry).
Emissions = 5.28g/h

TEST NUMBER 7

CALORIMETRY ROOM TEST SUMMARY

Efficiency and heat output tests were carried out on the MKII design at the Home Heating Laboratory on the 3/5/89.

FUEL: Briquettes.
Moisture: 15%.
Gross calorific value : 22.53 MJ/kg.

TEST DESCRIPTION

Air Intake Setting: LOW

Heater Modifications: Secondary air at hopper exit. No firebricks. Fan on.

Test conditions:	Barometric Pressure mmHg	Relative Humidity %
	760	70

Test data:

Time	Scale (fuel wt.) kg	Power output kW	Comments
0958	11.54	0.00	The heater was ignited with this weight of fuel and firestarters. Air intake was on high
1132	2.82	13.90	
1138	9.44	13.80	More briquettes were added to give a fuel weight of 9.44kg. The air intake was reduced to give a low burn rate.
1204	8.40	8.28	
1350	6.82	3.40	
1438	4.94	7.49	
1510	4.26	6.87	
1558	3.48	6.56	
1558	11.58	6.56	8.10kg of briquettes were added to the base weight of 3.48kg. This gave a total weight 11.58kg. This was the start of the test cycle.
1700	10.08	4.19	
1758	8.90	3.52	
1900	6.48	7.62	
2112	3.48	7.59	This point marked the end of the test cycle

OVERALL TEST CYCLE SUMMARY

Average power = 6.38kW
Overall efficiency = 65.9%
Burn rate = 1.55kg/h (wet)
1.32kg/h (dry).

TEST NUMBER 8

CALORIMETRY ROOM TEST SUMMARY

Efficiency and Emission rate tests were carried out on the MKII design at the Home Heating Laboratory on the 15/5/89.

FUEL: Briquettes.
Moisture: 15%.
Gross calorific value : 22.53 MJ/kg.

TEST DESCRIPTION

Air Intake Setting: MEDIUM

Heater Modifications: Secondary air at hopper exit and below grate. Firebricks were used. Fan on.

Test conditions:	Barometric Pressure mmHg	Relative Humidity %
	766	65

Test data:

Time	Scale (fuel wt.) kg	Power output kW	Comments
1018	10.92	0.00	The heater was ignited with firestarters.
1130	4.36	12.70	
1134	9.72	13.10	Reloaded heater with 5.36kg of briquettes and turned air intake to low.
1158	8.42	11.40	
1310	5.10	9.37	
1400	3.10/9.14	8.87	Using a base weight of 3.10kg a test cycle weight of 6.04kg testing began.
1510	6.78	7.50	
1534	5.76	9.15	
1606	4.58	9.69	
1656	3.10	10.20	End of cycle and test

OVERALL TEST CYCLE SUMMARY

Average power = 8.76kW
Overall efficiency = 67.2%
Burn rate = 2.08kg/h (wet)
1.77kg/h (dry).
Emissions = 3.02g/h

TEST NUMBER 9

CALORIMETRY ROOM TEST SUMMARY

Efficiency and Emission rate tests were carried out on the MKII design at the Home Heating Laboratory on the 16/5/89.

FUEL: Briquettes.
Moisture: 15%.
Gross calorific value : 22.53 MJ/kg.

TEST DESCRIPTION

Air Intake Setting: MEDIUM

Heater Modifications: Secondary air at hopper exit and below grate. Firebricks were used. Fan off.

Test conditions:	Barometric Pressure mmHg	Relative Humidity %
	764	76

Test data:

Time	Scale (fuel wt.) kg	Power output kW	Comments
0952	9.14	0.00	The heater was ignited with firestarters.
1100	6.16	9.78	Air intake was turned down to a medium setting
1158	4.68	4.64	Air in take opened up a little.
1338	2.80/9.00	5.39	The base weight was taken to be 2.80kg. The test cycle was commenced with a fuel weight of 6.2kg to give a total weight of 9.00kg.
1410	7.68	.7.04	
1448	5.88	8.12	
1540	4.18	8.42	
1610	3.50	7.68	
1658	2.80	6.64	At this point the original base weight was reached marking the end of the cycle and test.

OVERALL TEST CYCLE SUMMARY

Average power = 7.40kW
Overall efficiency = 64.2%
Burn rate = 1.84kg/h (wet)
1.56kg/h (dry).
Emissions = 2.66g/h

TEST NUMBER 10

CALORIMETRY ROOM TEST SUMMARY

Efficiency and Emission rate tests were carried out on the MKII design at the Home Heating Laboratory on the 17/5/89.

FUEL: Briquettes.
Moisture: 15%.
Gross calorific value : 22.53 MJ/kg.

TEST DESCRIPTION

Air Intake Setting: MEDIUM/LOW

Heater Modifications: Secondary air at hopper exit and below grate. Firebricks were used. Fan off.

Test conditions:	Barometric Pressure mmHg	Relative Humidity %
	764	72

Test data:

Time	Scale (fuel wt.) kg	Power output kW	Comments
1008	-	0.00	The heater was ignited with firestarters.
1120	4.32	9.98	
1122	7.40	10.01	The heater was reloaded with 3.08kg of briquettes and the air intake turned down.
1220	6.40	4.22	
1350	4.60/3.36	4.48	Some briquettes were removed from hopper to give a weight of 3.36kg.
1402	3.28/6.90	4.76	The base weight of thie test cycle was taken at 3.28kg. A cycle weight of 3.62kg was added and testing commenced.
1504	5.20	4.57	
1534	4.64	4.88	
1604	4.18	5.02	
1648	3.58	4.90	
1710	3.28	5.28	End of cycle and test.

OVERALL TEST CYCLE SUMMARY

Average power = 4.91kW
Overall efficiency = 67.9%
Burn rate = 1.16kg/h (wet)
0.99kg/h (dry).
Emissions = 10.45g/h

TEST NUMBER 11
CALORIMETRY ROOM TEST SUMMARY

Efficiency and Emission rate tests were carried out on the MKII design at the Home Heating Laboratory on the 5/6/89.

FUEL: Briquettės.
Moisture: 15%.
Gross calorific value : 22.53 MJ/kg.

TEST DESCRIPTION

Air Intake Setting: LOW

Heater Modifications: Preheated secondary air at hopper exit and below grate. Firebricks were used. Fan off.

Test conditions:

Barometric Pressure mmHg	Relative Humidity %
760	82

Test data:

Time	Scale (fuel wt.) kg	Power output kW	Comments
0950	9.20	0.00	The heater was ignited with firestarters.
1002	8.82	2.00	
1146	4.90/7.78	7.01	Reloaded the heater with 2.88kg to give a weight of 7.78kg. The air intake, which was on high was turned down to a low setting.
1320	6.16	3.29	
1332	6.06/3.72	3.16	At this point the heat output and burn rate had stabilized. Since it would have taken several hours for the base weight to be reached some briquettes were removed from the hopper.
1412	3.24/0.00	3.87	The scales were tared at a weight of 3.24kg.
1414	3.52	3.87	The test cycle was started with 3.52kg of briquettes.
1444	2.78	3.96	
1514	2.24	3.53	
1544	1.88	3.17	
1630	1.40	2.92	
1744	0.62	3.26	
1814	0.22	3.91	
1838	0.00	3.93	This was the end of the cycle and the test.

OVERALL TEST CYCLE SUMMARY

Average power = 3.41kW
Overall efficiency = 68.6%
Burn rate = 0.79kg/h (wet)
0.69kg/h (dry).
Emissions = 5.31g/h

TEST NUMBER 12

CALORIMETRY ROOM TEST SUMMARY

Efficiency and Emission rate tests were carried out on the MKII design at the Home Heating Laboratory on the 6/6/89.

FUEL: Briquettes.
Moisture: 15%.
Gross calorific value : 22.53 MJ/kg.

TEST DESCRIPTION

Air Intake Setting: MEDIUM/LOW

Heater Modifications: Preheated secondary air at hopper exit and below grate. Firebricks were used. Fan off.

Test conditions:

Barometric Pressure mmHg	Relative Humidity %
750	72

Test data:

Time	Scale (fuel wt.) kg	Power output kW	Comments
1050	7.00	0.00	The heater was ignited with firestarters.
1110	10.00	2.06	More briquettes added.
1248	3.18/0.00	11.8	Scales were tared at 3.18kg.
1248	4.28	11.8	Air intake turned down to low.
1348	2.30	5.98	
1438	0.32	4.83	
1502	0.00/3.02	5.39	Test cycle started at this point.
1602	1.62	4.88	
1632	1.10	4.97	
1732	0.26	4.97	
1754	0.00	5.17	End of cycle and test.

OVERALL TEST CYCLE SUMMARY

Average power = 4.92kW
Overall efficiency = 75.0%
Burn rate = 1.05kg/h (wet)
0.89kg/h (dry).
Emissions = 3.77g/h

TEST NUMBER 13

CALORIMETRY ROOM TEST SUMMARY

Efficiency and Emission rate tests were carried out on the MKII design at the Home Heating Laboratory on the 7/6/89.

FUEL: Briquettes.
Moisture: 15%.
Gross calorific value : 22.53 MJ/kg.

TEST DESCRIPTION

Air Intake Setting: MEDIUM

Heater Modifications: Preheated secondary air at hopper exit and below grate. Firebricks were used. Fan off.

Test conditions:

Barometric Pressure mmHg	Relative Humidity %
750	74

Test data:

Time	Scale (fuel wt.) kg	Power output kW	Comments
1000	4.30	0.00	The heater was ignited with firestarters.
1036	8.87	2.76	Added more briquettes and adjusted air intake medium setting.
1128	5.24	7.09	
1140	4.66	7.85	
1156	7.84	7.98	Added more fuel.
1216	6.94	7.70	
1258	5.62	6.87	
1354	3.94	7.38	
1406	3.12	8.58	
1406	0.00	8.58	Tared the scales
1406	4.58	8.58	Added test cycle load
1438	3.20	8.02	
1538	1.54	7.25	
1644	0.00	8.04	The test cycle ended at this point.

OVERALL TEST CYCLE SUMMARY

Average power = 7.75kW
Overall efficiency = 71.2%
Burn rate = 1.74kg/h (wet)
1.48kg/h (dry).
Emissions = 2.97g/h

TEST NUMBER 14

CALORIMETRY ROOM TEST SUMMARY

Efficiency and Emission rate tests were carried out on the MKII design at the Home Heating Laboratory on the 8/6/89.

FUEL: Briquettes.
Moisture: 15%.
Gross calorific value : 22.53 MJ/kg.

TEST DESCRIPTION

Air Intake Setting: HIGH

Heater Modifications: Preheated secondary air at hopper exit and below grate. Firebricks were used. Fan on.

Test conditions:

Barometric Pressure mmHg	Relative Humidity %
751	60

Test data:

Time	Scale (fuel wt.) kg	Power output kW	Comments
1000	10.18	0.00	The heater was ignited with firestarters.
1018	9.00	3.18	Turned the convection fan on
1118	4.16	10.80	
1120	9.70	10.70	Reloaded hopper with 5.54kh of briquettes.
1200	7.24	11.00	
1204	9.20	10.90	Reloaded with 1.96kg
1352	3.10	14.10	Had difficulty in maintaining a 12pa air duct pressure due to the low atmospheric pressure of 747mmHg. The program was stopped and re-run with a 10pa air duct pressure and 747 mmHg.
1358	3.02/0.00	13.30	The scales were tared at a base weight of 3.02kg
1358	5.14	13.30	and 5.14kg of fuel added to hopper and test cycle commenced
1414	4.00	12.70	
1430	3.00	12.50	
1500	1.18	13.30	
1528	0.00	13.30	At this point the cycle and test ended.

OVERALL TEST CYCLE SUMMARY

Average power = 13.33kW
Overall efficiency = 62.3%
Burn rate = 3.42kg/h (wet)
2.91kg/h (dry).
Emissions = 2.38g/h